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A Cognitive Framework for Information Visualization: Annotated Bibliography

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U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
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Gaithersburg, MD 20899-0001

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This document is the final report on work performed under Contract #60NANB6D0125, titled "Evaluating the Use of 3-D Visualization to Identify Structure in Information Spaces" for the National Institute of Standards and Technology (NIST).

The purpose of this work was to provide a framework for the evaluation of visual interfaces in support of access to large databases of abstract information ("information visualization"), with emphasis on three-dimensional representations. This framework is based on current research in human cognition and perception.

This work is part of a larger effort by the Visualization and Virtual Reality Group within NIST's Information Technology Laboratory (ITL) to develop methodologies and test corpora for the evaluation of information visualization techniques for large complex document collections.

For further information, please contact Dr. Sharon Laskowski, (laskowski@nist.gov) or see: http://www.nist.gov/itl/div894/vvrg/.

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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary

TECHNOLOGY ADMINISTRATION
Gary R. Bachula, Acting Under Secretary
for Technology

NATIONAL INSTITUTE OF STANDARDS
AND TECHNOLOGY
Raymond G. Kammer, Director

Bibliography Overview

Selection. This bibliography consists of selected readings that provide a preliminary cognitive framework for the design and evaluation of information visualization. Since information visualization is in the early stages of development, articles are drawn from the core areas of cognitive science, psychology, and computer science. The articles outline foundations of perception and reasoning, provide illustrative examples, or compare specific systems. Although many relevant component issues are addressed, few references systematically relate basic theory to the design of information visualization. Throughout the bibliography, emphasis is given to visualization, especially in three dimensions. Priority is given to recent publications; however, older articles are included if they are especially relevant or provide a basis for subsequent research.

Organization. The document has five sections. The first section emphasizes basic issues in perception and cognition that underlie design. The second section examines general interface and visualization issues that are relevant to a wide range of design questions. The third section, which constitutes the core of the bibliography, lists articles that support various design guidelines. This section is structured around a revision to human-computer interface (HCI) design guidelines developed for a more general context (Sebrechts, Knott, & Etgen, 1997)* and modified for visualization issues. The fourth section on interface evaluation includes articles that specify alternative means of evaluating interface effectiveness. The last section presents a number of interesting example cases of visualization, especially in 3D. Articles are included under the section for which they have greatest relevance. Following each reference, keywords from the relevant section headings and subheadings are included in brackets in the order in which they occur in the table of contents.

Sources. The abstracts accompanying each article are drawn from several sources: those from the American Psychological Association (APA) PsycLIT database are accompanied by their copyright notice; others are drawn, with some modification, from the individual documents or Gary Perlman's online HCI Bibliography Project, (http://www.tu-graz.ac.at/HCIbib.bkrep); abstracts not available from those sources were generated by the Visualization Research Team at The Catholic University of America. In general, workshops, symposia, and tutorials are not included unless the abstract itself provides relevant information not contained elsewhere.

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* Copies of the HCI guidelines may be obtained from Marc M. Sebrechts, Department of Psychology, The Catholic University of America, Washington DC 20064; (202) 319-5750; Sebrechts@cua.edu.

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A. Perception and Evaluation of the System: Make it easy for the user to perceive and evaluate the structure and state of the system. ---------- 24

A.1. Visibility: Make the state of the system, available interactions, and consequences of user action readily apparent, minimizing the need for the user to remember or infer information. ---------- 24

A.2. Identifiability: Make the meaning of an object or statement clear and distinct from other objects or statements. ---------- 28
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B. Development and Execution of Action Sequences: Enable the user to achieve goals, perform tasks, and execute commands easily ---------- 59

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Navigation ---------- 59

B.2. Input Compatibility: Provide intuitive, natural mapping between input devices, the visual interface, and the user's task. ---------- 66

B.3. Traceability, Recoverability and Resilience: Provide a means to retrieve previously used sequences or information, recover from unintended or incorrect actions, and assist users in avoiding results from which they cannot recover. ---------- 71

C. Context and Relations: Situate interactions within the broader context of the computer system and the user's experience ---------- 74

C.1. Consistency: Make representations and functions common within and across tasks. ---------- 74

C.2. Familiarity: Use familiar terms, attributes, and relations among objects ---------- 77

C.3. Situation: Make clear the context in which an object or action occurs and the constraints on its use ---------- 79

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I. Cognition and Perception

Andersen, G. J. (1986). "Perception of self-motion: Psychophysical and computational approaches." Psychological Bulletin **99**(1): 52-65
[Cognition and Perception].

Visually induced perception of self-motion has been studied from 2 perspectives--one concerned with psychophysical relations between the visual stimulus and the perception of self-motion and a 2nd concerned with computational relations between changing 2-dimensional projections and observer motion in a 3-dimensional environment. Results from these 2 perspectives are analyzed in terms of the occurrence of perceived rotation and translation, the perceived direction of self-motion, eye movements, focal/ambient theory, and optic flow. The lack of interaction between the different approaches is noted, and it is argued that further research, integrating these 2 approaches, is needed for a more complete understanding of the distinctions between optical transformations that result in perceived object motion and those that result in perceived self-motion. (75 ref) (PsycLIT Database Copyright 1986 American Psychological Assn, all rights reserved)

Ashby, F. G. (1992). Multidimensional Models of Perception and Cognition. Hillsdale, NJ, Erlbaum
[Cognition and Perception].

An excellent collection of theoretically-oriented research on human pattern recognition. The chapters focus on the problem of multidimensional integration and favor a quantitative approach.

Barfield, W., G. Salvendy and J. Foley (1989). "An Analogue and Propositional Hybrid Model for the Perception of Computer Generated Graphical Images." Behaviour and Information Technology **8**(4): 257-272
[Cognition and Perception, Structural Integrity].

This research investigated two alternative models, analogue and propositional, which describe how three-dimensional (3-D) graphical images are represented and stored in human memory. In order to differentiate between the two models, three separate experiments were performed using a variation of the Shepard-Metzler mental rotation paradigm (Shepard and Metzler 1971). For each experiment, the effects of three independent variables on the performance of a 'mental rotation' task were examined: (a) three levels of figure complexity, (b) three axes of rotation and (c) four angles of rotation. The subjects' task was to compare specific angle, axis or depth versus picture plane rotations for pairs (rotated and non-rotated versions) of 3-D graphic figures displayed on a CRT. The results indicated that response times varied depending on level of figure complexity, axis or angle of rotation. A new hybrid model integrating components of both the analogue and propositional positions is proposed to explain the reaction time data. In this model, analogue processes occur when processing requirements for cognitive tasks are low, whereas propositional processes occur when processing requirements are high. Implications of the results for the internal representation of 3-D images in human memory and for the design of graphic work stations are discussed.

Bennett, K. B. and J. M. Flach (1992). "Graphical displays: Implications for divided attention, focused attention, and problem solving. Special Issue: Visual displays." Human Factors **34**(5): 513-533
[Cognition and Perception].

Considers the issue of whether or not in display design a single display format can achieve the dual design goals of supporting performance at integrated and focused tasks. One relevant perspective is the basic research on attention and object perception, which concentrates on the interaction between visual features and processing capabilities. The principles of configurality are discussed, with the conclusion that they support the possibility of achieving the dual design goals. These considerations are necessary, but not sufficient for effective display design. Graphic displays map information from a domain into visual features; the tasks to be completed are defined in terms of the domain, not in terms of the visual features alone. This subtle but important difference is pertinent to focused attention, divided attention, and problem solving. Research investigating alternative display formats is reviewed. (PsycLIT Database Copyright 1993 American Psychological Assn, all rights reserved)

Bjork, E., L., & Bjork, Robert A. (1996). Memory. New York, Academic Press.
[Cognition and Perception].

This handbook and reference tool provides a synopsis of the research and literature on human memory including comprehensive chapters on basic theory. The text discusses storage and access of information in both short-term and long-term memory: how we control, monitor, and enhance memory; individual differences in mnemonic ability; and the processes of retireval and retention, including eyewitness testimony and training and instruction

Bovair, S., D. E. Kieras and P. G. Polson (1990). "The acquisition and performance of text-editing skill: A cognitive complexity analysis." Human Computer Interaction **5**(1): 1-48
[Cognition and Perception].

Describes principles for constructing cognitive complexity models (CCMs) of a user's procedural knowledge. The CCM for an experimental text editor is presented and tested as a complete example of a model constructed using the principles. In Exp 1, predictions from applying the transfer model were tested against 90 Ss' performance as they learned the editor. In Exp 2, the execution model's predictions for how long it should take to perform a set of editing tasks were tested against 8 Ss' performance on the tasks, after training and after 8 days of practice. Results support the cognitive complexity theory of D. E. Kieras and P. G. Polson (see PA, Vol 73:2697). The model predicted learning and execution data, accounting for substantial variance in learning and execution time. (PsycLIT Database Copyright 1991 American Psychological Assn, all rights reserved)

Bregman, A. S. (1990). Auditory Scene Analysis: The Perceptual Organization of Sound. Cambridge, MA, MIT Press.
[Cognition and Perception].

Auditory Scene Analysis addresses the problem of hearing complex auditory environments, using a series of creative analogies to describe the process required of the human auditory system as it analyzes mixtures of sounds to recover descriptions of individual sounds. In a unified and comprehensive way, Bregman establishes a theoretical framework that integrates his findings with an unusually wide range of previous research in psychoacoustics, speech perception, music theory and composition, and computer modeling.

Cowan, N. (1995). Attention and Memory: An Integrated Framework. New York, Oxford University Press
[Cognition and Perception].

This book brings together and assesses past and present research on information processing, and formulates a new general model of this entire system. Throughout his discussion, Cowan emphasizes that memory and attention cannot be considered independently and presents new research in psychophysiology, visual perception, cognitive development, and individual differences to support his thesis. This book offers both a review of the literature and a new model.

Davi, M. and D. R. Proffitt (1993). “Frames of reference and distinctive figural characteristics affect shape perception.” Journal of Experimental Psychology Human Perception and Performance **19**(4): 867-877
[Cognition and Perception, Identifiability: Perceptual Grouping].

In 4 experiments it was found that global frameworks and local distinctive figural characteristics influenced the perception of shape and of pointing. In Exps 1 and 2, Ss were asked to mark the center of the middle figure in array of 3 aligned figures (either triangles or squares). Displacements of the center indicated a perceived deformation of the shapes. In Exp 3, Ss were asked to adjust the height of triangles in arrays similar to those in Exp 1. Height adjustments made along the axis of apparent pointing resulted in extents that were shorter than the height necessary to form equilateral triangles. In Exp 4, stimuli were isosceles triangles in which the apparent distortion had been nulled; however, Ss continued to perceive them as pointing in a direction consistent with their alignment, and hence shape distortion cannot be the cause of pointing. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

DeValois, R., L., 7 DeValois, Karen, K. (1990). Spatial Vision. New York, Oxford University Press
[Cognition and Perception].

This book is an integrated survey of what is known about how the primate visual system captures and encodes information about spatial patterns, including information about the sizes, shapes, and locations of objects and the textures of surfaces. Useful for the reader interested in the biological basis of spatial vision.

Durgin, F. H., D. R. Proffitt, T. J. Olson and K. S. Reinke (1995). “Comparing depth from motion with depth from binocular disparity.” Journal of Experimental Psychology Human Perception and Performance **21**(3): 679-699

[Cognition and Perception].

The accuracy of depth judgments that are based on binocular disparity or structure from motion (motion parallax and object rotation) was studied in 3 experiments. In Experiment 1, depth judgments were recorded for computer simulations of cones specified by binocular disparity, motion parallax, or stereokinesis. In Experiment 2, judgments were recorded for real cones in a structured environment, with depth information from binocular disparity, motion parallax, or object rotation about the y -axis. In both of these experiments, judgments from binocular disparity information were quite accurate, but judgments on the basis of geometrically equivalent or more robust motion information reflected poor recovery of quantitative depth information. A 3rd experiment demonstrated stereoscopic depth constancy for distances of 1 to 3 m using real objects in a well-illuminated, structured viewing environment in which monocular depth cues (e.g., shading) were minimized. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

Epstein, W., & Rogers, Sheena . (1995). Perception of Space and Motion. New York, Academic Press
[Cognition and Perception].

Provides a comprehensive review of research in perception and vision, looking at new developments in the use of sound and touch in perceiving space and motion and in the perception of structure from motion, spatial layout, and information obtained in static and dynamic stimulation. Other topics include the perception of pictorial space, and visual perception and control. Of interest to psychologists, cognitive scientists, and natural scientists. Annotation copyright Book News, Inc. Portland, Or.

Estes, W. K. (1994). Classification and Cognition. New York, Oxford University Press
[Cognition and Perception].

Understanding classification is a major challenge for formulating theories of both human cognition and artificial intelligence. Classification is a human mental activity which covers such diverse things as forming concepts, categorizing medical patients, recognizing an acquaintance, or discriminating phonetic components of a language. This book considers both previous theories and new research and comes up with a new core model which it proposes as the basis of all forms of classification. Two versions of this model are developed, one based on symbol-processing, and one on connectionist architecture, and it is suggested that modules of each type of model coexist in the human cognitive system, competing for control of behavioural output.

Fisk, A. E., & Rogers, Wendy, A. (1996). Handbook of Human Factors and the Older Adult. New York, Academic Press
[Cognition and Perception].

Within developed countries, the elderly population--people aged 75 and older--is expanding faster than its younger counterpart. This change in demographics creates a need for understanding ergonomics with respect to the aged user in the design of products, transportation, safety, leisure activity aids, and work and home environments. The Handbook of Human Factors and the Older Adult provides a comprehensive sourcebook for information on the interface of gerontology and ergonomics. The Handbook discusses practical applications, theory, and research in this dynamic area. This book is divided into two sections; Section I covers how the neuropsychology and physiology of aging relates to issues of human factors, while Section II addresses applications of human factor research to the older population and specific environments.

Gardner, H. (1993). Multiple Intelligences: The theory in practice. New York, Basic Books
[Cognition and Perception].

This extremely influential book on the nature of intelligence extends the author's earlier work on the topic. The author's theory challenges the traditional psychological view of intelligence as a single capacity that drives logical and mathematical thought. Instead, it proposes that all individuals possess seven independent intelligences. These, in combination, enable people to solve problems or fashion products with varying levels of skill.

Garner, W. R. (1978). Aspects of a Stimulus: Features, Dimensions, and Configurations. Cognition and Categorizations. E. Rosch and B. lloyd. Hillsdale, NJ, Lawrence Erlbaum Associates.
[Cognition and Perception].

This article serves to define basic properties and relations among stimulus components. It provides a frequently used basic perceptual taxonomy.

Gilhooly, K. J. (1996). Thinking: Directed, Undirected and Creative. New York, Academic Press.
[Cognition and Perception].

This book is the third edition of K.J. Gilhoolys widely adopted text on the intriguing and challenging topic of thinking. It provides an up-to-date review of a wide range of research and theory aimed at increasing our understanding of thought processes.

Gillan, D. J. and R. Lewis (1994). “A componential model of human interaction with graphs: I. Linear regression modeling.” Human Factors **36**(3): 419-440
[Cognition and Perception].

Two experiments investigated the prediction that response time will be linearly related to the number of processing steps according to the Mixed Arithmetic-Perceptual (MA-P) model. A total of 25 Ss used line graphs, scatter plots, and stacked bar graphs to answer comparison questions and questions requiring arithmetic calculations. A 1-parameter version of the model (with equal weights for all components) and a 2-parameter version (with different weights for arithmetic and nonarithmetic processes) accounted for 76-85% of individual Ss' variance in response time and 61-68% of the variance taken across all Ss. Possible modifications in the MA-P model, alternative models, and design implications from the MA-P model are discussed. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

Gillan, D. J. and E. H. Richman (1994). “Minimalism and the syntax of graphs.” Human Factors **36**(4): 619-644
[Cognition and Perception].

Examined E. R. Tufte's (1983) syntactic rule that graphs should have maximal data-ink ratios produced by erasing non-data-ink and redundant data-ink in 4 experiments consisting of 17 undergraduates in each experiment. Exp 1 examined the data-ink ratios of bar and line graphs and their effects on accuracy and response times. Results showed that an increase on the data-ink ratio benefitted speed and accuracy. Exps 2, 3A, and 3B investigated the effects of ink on the syntactic elements of a graph based on the function and location of the element. Results indicated that ink can be helpful or detrimental to the graph reader depending on the function and location of the ink, the user's task, type of graph, and the physical relations among graphical elements. The discussion focuses on psychological principles of human graph interaction and those underlying the effects of each syntactic element. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

Goh, S. K. and B. G. Coury (1994). “Incorporating the effect of display formats in cognitive modelling. Special Issue: Festschrift in honour of Professor E. Nigel Corlett.” Ergonomics **37**(4): 725-745
[Cognition and Perception].

Integrated the effects of display formats into cognitive modeling by determining the locus of that effect in information processing strategies. Cognitive models of information processing strategies were constructed from verbal protocols obtained during data collection with 36 Ss. The models of 6 Ss (2 from each display group) were selected for analysis. Creating the models required 5 steps: transcribe the protocols, encapsulate descriptors, encode protocols, derive models, and identify strategies. Analysis utilized elementary information processes describing a set of cognitive operations that represent the lowest level of task decomposition. Results show how the models must be adjusted to account for the differences in performance related to a specific type of display format. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

Hecht, H. and D. R. Proffitt (1991). “Apparent extended body motions in depth.” Journal of Experimental Psychology Human Perception and Performance **17**(4): 1090-1103
[Cognition and Perception].

Five experiments were designed to investigate the influence of 3-dimensional (3-D) orientation change on apparent motion. Projections of an orientation-specific 3-D object were sequentially flashed in different locations and at different orientations. Such an occurrence could be resolved by perceiving a rotational motion in depth around an axis external to the object. Consistent with this proposal, it was found that observers perceived curved paths in depth. Although the magnitude of perceived trajectory curvature often fell short of that required for rotational motions in depth (3-D circularity), judgments of the slant of the virtual plane on which apparent motions occurred were quite close to the predictions of a model that proposes circular paths in depth. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Hildreth, E. C. (1982). The Measurement of Visual Motion. Cambridge, MA, MIT Press. [Cognition and Perception].

This book examines the measurement of movement in the changing image that reaches the eye and addresses how the brain extracts information about the structure of our surroundings. It focuses on the nature of the computations necessary to perform this analysis by any vision system, biological or artificial.

Hoffman, D. D. and W. A. Richards (1985). Parts of Recognition. Computational Models of Cognition and Perceptual. S. Pinker. London, England, The MIT Press: 65-96 [Cognition and Perception].

This chapter advances the view that object recognition occurs in part through the decomposition of shapes into parts. Transversality serves as a basis for defining part boundaries. Parts and spatial relations are examined as indices for shape memory.

Hollands, J. G. and I. Spence (1992). "Judgments of change and proportion in graphical perception." Human Factors **34**(3): 313-334
[Cognition and Perception].

60 university students judged change and proportion when viewing graphs in 2 experiments. Change was judged more quickly and accurately with line and bar graphs than with pie charts or tiered bar graphs, and this difference was larger when the rate of change was smaller. Without a graduated scale, proportion was judged more quickly and accurately with pie charts and divided bar graphs than with line or bar graphs. Perception is direct when it requires simpler or fewer mental operations. The authors propose that perception of change is direct with line and bar graphs, whereas perception of proportion is direct with pie charts and divided bar graphs. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Joseph, J. E. and D. R. Proffitt (1996). "Semantic versus perceptual influences of color in object recognition." Journal of Experimental Psychology Learning, Memory, and Cognition **22**(2): 407-429
[Cognition and Perception].

The influence of color as a surface feature versus its influence as stored knowledge in object recognition was assessed. Participants decided whether a briefly presented and masked picture matched a test name. For pictures and words referring to similarly shaped objects, semantic color similarity (SCS) was present when picture and word shared the same prototypical color (e.g., purple apple followed by cherry). Perceptual color similarity (PCS) was present when the surface color of the picture matched the prototypical color of the named object (e.g., purple apple followed by blueberry). Response interference was primarily due to SCS, despite the fact that participants based similarity ratings on PCS. When uncolored objects were used, SCS interference still occurred, implying that the influence of SCS did not depend on the presence of surface color. The results indicate that, relative to surface color, stored color knowledge was more influential in object recognition. (PsycLIT Database Copyright 1996 American Psychological Assn, all rights reserved)

Julesz, B. (1971). Foundations of Cyclopean Perception. Chicago, University of Chicago Press
[Cognition and Perception].

Although there have been many recent findings on this topic, this book remains the classic in human stereoscopic vision.

Kaiser, M. K. and J. B. Calderone (1991). "Factors influencing perceived angular velocity." Perception and Psychophysics **50**(5): 428-434
[Cognition and Perception].

Investigated the human ability to process angular kinematics and examined factors likely to influence angular velocity perception, particularly (1) the extent to which perceived angular velocity is determined by edge transitions of surface elements, (2) the extent to which angular velocity estimates are influenced by instantaneous linear velocities of surface elements, and (3) whether element-velocity effects are related to 3-dimensional (3-D) tangential velocities or to 2-dimensional (2-D) image velocities. In 8 adult Ss, edge-transition rate biased angular velocity estimates only when edges were highly salient. Element velocities influenced perceived angular velocity; this bias was related to 2-D image velocity rather than 3-D tangential velocity. Despite these biases, judgments were most strongly determined by true angular velocity. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Kaiser, M. K., M. J. Montegut and D. R. Proffitt (1995). "Rotational and translational components of motion parallax: Observers' sensitivity and implications for three-dimensional computer graphics." Journal of Experimental Psychology Applied **1**(4): 321-331
[Cognition and Perception].

The motion of objects during motion parallax can be decomposed into 2 observer-relative components: translation and rotation. The depth ratio of objects in the visual field is specified by the inverse ratio of their angular displacement (from translation) or equivalently by the inverse ratio of their rotations. Despite the equal mathematical status of these 2 information sources, it was predicted that observers would be far more sensitive to the translational than rotational components. Such a differential sensitivity is implicitly assumed by the computer graphics technique billboarding , in which 3-dimensional (3-D) objects are drawn as planar forms (i.e., billboards) maintained normal to the line of sight. In 3 experiments, observers were found to be consistently less sensitive to rotational anomalies. The implications of these findings for kinetic depth effect displays and billboarding techniques are discussed. (PsycLIT Database Copyright 1996 American Psychological Assn, all rights reserved)

Kaiser, M. K., D. R. Proffitt, S. M. Whelan and H. Hecht (1992). "Influence of animation on dynamical judgments." Journal of Experimental Psychology Human Perception and Performance **18**(3): 669-689
[Cognition and Perception].

The motions of objects in the environment reflect underlying dynamical constraints and regularities. The conditions under which people are sensitive to natural dynamics are considered. In particular, the article considers what determines whether observers can distinguish canonical and anomalous dynamics when viewing ongoing events. The extent to which such perceptual appreciations are integrated with and influence commonsense reasoning about mechanical events is examined. It is concluded that animation evokes accurate dynamical intuitions when there is only 1 dimension of information that is of dynamical relevance. This advantage is lost when the observed motion reflects higher dimension dynamics or when the kinematic information is removed or degraded. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Kosslyn, S. M. (1994). Image and Brain: The Resolution of the Imagery Debate. Cambridge, MA, MIT Press.
[Cognition and Perception].

This work integrates a twenty-year research program on the nature of high-level vision and mental imagery. Image and Brain marshals insights and empirical results from computer vision, neuroscience, and cognitive science to develop a general theory of visual mental imagery, its relation to visual perception, and its implementation in the human brain. It offers a resolution to the long-standing debate about the nature of the internal representation of visual mental imagery. Kosslyn reviews evidence that perception and representation are inextricably linked, and goes on to show how "quasi-pictorial" events in the brain are generated, interpreted, and used in cognition. The theory is tested with brain-scanning techniques that provide stronger evidence than has been possible in the past.

Martin, R. C. and J. R. Pomerantz (1978). "Visual discrimination of texture." Perception and Psychophysics **24**(5): 420-428
[Cognition and Perception].

B. Julesz (1975) proposed a theory of texture discrimination, based on an order statistics principle, which states that no 2 textures can be perceptually discriminated if they have identical 2nd-order statistics. The results of 4 experiments (using a total of 27 college students) demonstrate that this principle is not adequate to predict visual texture discriminability. Both letter and dot micropatterns were used to create texture pairs that either differed or were identical with respect to 2nd-order statistics. S's task was to decide which quadrant of an array contained a disparate texture. In Exps I-III, when controlling for spatial overlap, texture pairs having identical 2nd-order statistics were discriminated more quickly than similar texture pairs having different 2nd-order statistics, in contradiction to the principle. Although a significant effect in the direction predicted by the order statistics principle was found in Exp IV for texture pairs created from the dot micropatterns, other factors, such as spatial overlap, border differences, and goodness of pattern, must also be considered in predicting texture discriminability. (11 ref) (PsycLIT Database Copyright 1980 American Psychological Assn, all rights reserved)

McNamara, T. P. (1986). "Mental representations of spatial relations." Cognitive Psychology **18**(1): 87-121
[Cognition and Perception].

Tested 3 classes of theories of the mental representation of spatial relations. Nonhierarchical theories propose that spatial relations among objects in an environment are mentally represented in networks or in imagelike, analog formats. Hierarchical theories propose that different regions of an environment are stored in different branches of a graph-theoretic tree. These theories can be divided into 2 classes of subtheories: Strongly hierarchical theories maximize storage efficiency by encoding only those spatial relations needed to represent a layout accurately; partially hierarchical theories predict redundancy in the representation. These 3 classes of theories were tested by having 72 undergraduates learn the locations of actual objects in spatial layouts or the locations of objects on maps of those layouts. After learning the layouts or maps, Ss participated in item recognition, direction judgments, and euclidian distance estimation. Results were sensitive (a) to whether objects were in the same region or in different regions and (b) to the euclidean distances between pairs of objects. Findings support partially hierarchical theories of spatial representations. (70 ref) (PsycLIT Database Copyright 1986 American Psychological Assn, all rights reserved)

McNamara, T. P. and L. L. LeSueur (1989). "Mental representations of spatial and nonspatial relations." Quarterly Journal of Experimental Psychology Human Experimental Psychology **41**(2-a): 215-233
[Cognition and Perception].

Four experiments with 120 Ss investigated the representation and integration in memory of spatial and nonspatial relations. Ss learned 2-dimensional spatial arrays in which critical pairs of object names were semantically related (Exp 1), semantically and episodically related (Exp 2), or just episodically related (Exp 3a and 3b). Episodic relatedness was established in a pair-associate learning task that preceded array learning. After learning an array, Ss participated in 2 tasks: item recognition, in which the measure of interest was priming; and distance estimation. Results indicate that nonspatial relations influenced the probability of encoding spatial relations between locations but did not lead to distorted spatial memories. (PsycLIT Database Copyright 1989 American Psychological Assn, all rights reserved)

McNamara, T. P., R. Ratcliff and G. McKoon (1984). "The mental representation of knowledge acquired from maps." Journal of Experimental Psychology Learning, Memory, and Cognition **10**(4): 723-732
[Cognition and Perception].

Investigated the mental representation of knowledge acquired from maps using recognition priming and distance estimation with 30 college students. In Exp I, recognition priming showed that cities close in route distance primed each other more than cities far in route distance, even when Euclidean distance was equated. Exp II showed that this finding was robust and not an artifact of the way Ss learned the maps. Distance estimations in Exp I supported the priming results. These results indicate that psychological distance in cognitive maps is primarily dependent on route distance rather than Euclidean distance. Two explanations for these findings assume that (1) spatial knowledge is mentally represented in analog form with continuously varying properties, or (2) spatial knowledge is mentally represented in a propositional format. (25 ref) (PsycLIT Database Copyright 1985 American Psychological Assn, all rights reserved)

Pinker, S. and R. A. Finke (1980). “Emergent two-dimensional patterns in images rotated in depth.” Journal of Experimental Psychology Human Perception and Performance **6**(2): 244-264
[Cognition and Perception].

In 4 experiments, a total of 78 experimental Ss formed mental images of a set of objects hanging in a clear cylinder and mentally rotated their images as they physically rotated the cylinder by various amounts. Ss performed 4 tasks, each demanding the ability to "see" the 2-dimensional patterns that should emerge in their images if the images depicted the new perspective view accurately--(a) Ss described the 2-dimensional geometric shape that the imagined objects formed in an image rotated 90Deg.; (b) they "scanned" horizontally from one imagined object to another in a rotated image; (c) they physically rotated the empty cylinder together with their image until 2 of the imagined objects were vertically aligned; and (d) they adjusted a marker to line up with a single object in a rotated image. Results suggest that Ss' images accurately displayed the 2-dimensional patterns emerging from a rotation in depth. However, the amount by which Ss rotated their image differed systematically from the amount specified by the experimenter. Results are discussed in the context of a model of the mental representation of physical space that incorporates 2 types of structures, one representing the 3-dimensional layout of a scene, and the other representing the 2-dimensional perspective view of the scene from a given vantage point. (29 ref) (PsycLIT Database Copyright 1981 American Psychological Assn, all rights reserved)

Pinker, S. (1984). Visual Cognition. Cambridge, Massachusetts, MIT Press
[Cognition and Perception].

This book offers an overview of issues and theories of visual cognition including object recognition, the computational architectures and complexity of visual cognition, and theories of mental imagery.

Proffitt, D. R., I. Rock, H. Hecht and J. Schubert (1992). “Stereokinetic effect and its relation to the kinetic depth effect.” Journal of Experimental Psychology Human Perception and Performance 18(1): 3-21
[Cognition and Perception].

The stereokinetic effect (SKE) has been defined and studied by nested circular patterns rotating on a turntable. Circles must appear not to rotate as they revolve, which in turn results in their appearing to translate relative to one another. A powerful illusion of object depth results even though the individual circles do not undergo an appropriate foreshortening consistent with their apparent changes in slant. It is suggested and tested that the SKE is based on the changing positions between the nested contours despite the absence of any change within each contour, whereas the kinetic depth effect (KDE) entails both kinds of change. It follows that a turntable method of presentation is not necessary, and between-contour transformations can be stimulated by computer animation. Displays consisting of simple translations were shown to evoke robust depth impressions as were patterns consisting of contours of varying shapes. Comparisons of the depth, compellingness, and rigidity of matched SKE and KDE displays are reported. The SKE is taken to be paradigmatic for how the visual system perceives depth when observing small object rotations that occur in everyday situations. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Smith, K. and P. A. Hancock (1995). "Situation awareness is adaptive, externally directed consciousness. Special Issue: Situation awareness." Human Factors **37**(1): 137-148 [Cognition and Perception].

Defines situation awareness (SA) as adaptive, externally directed consciousness. The source of goals with respect to SA is a normative arbiter in the task environment (i.e., the behavior that SA generates must be directed at an external goal). SA is the invariant at the core of the agent's perception-action cycle that supports skilled performance (i.e., relationships among factors or dimensions in the environment determine what the agent must know and do to achieve the goals specified by the external arbiter). A construct called the risk space (RS) is introduced to represent the invariant relations in the environment that enable the agent to adapt to novel situations and to attain prespecified goals. A specific example in commercial aircraft operations is used to illustrate the concept of RS. RS may be generalized to many different means of navigation. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

Wasserman, G. S. (1990). Color Vision : An Historical Introduction. New York, Wiley [Cognition and Perception].

This book reviews what is known about the perception of color and how this knowledge emerged historically.

Wickens, C. D. (1992). Engineering psychology and human performance (2nd ed.). New York, NY, HarperCollins Publishers
[Cognition and Perception].

(from the preface) "Over the past five decades, tremendous gains have been made in understanding and modeling human information processing. My goal is to show how these theoretical advances have been, or might be, applied to improving human-machine interactions. /// The 12 chapters of the book span a wide range of human performance components. Following the introduction in Chapter 1, in which engineering psychology is put into the broader framework of human factors and system design, Chapters 2 through 7 deal with perception, attention, memory, learning, and decision making, emphasizing the potential applications of these areas of cognitive psychology. Chapters 8 through 11 cover reaction time, action, time-sharing, error, stress, and manual control, thereby addressing areas that are more traditionally associated with the engineering field. Finally, Chapter 12 is systems-oriented, discussing process control and automation. This chapter shows how many of the principles explained in earlier chapters are pertinent to one specific application of rapidly growing importance. /// My intended audience, therefore, is (1) the student in psychology,... (2) the engineering student,... and (3) the actual practioner in engineering psychology, human performance, and human factors engineering... ."

II. Interface Design and Visualization

Allen, B. (1996). Toward a User-Centered Approach to Information Systems. New York, Academic Press
[Interface Design]

The user-centered approach is central to the creation of usable information systems, services, and institutions. Information system design should derive from user research into information needs, tasks accomplished in meeting those needs, and resources used in the tasks. Information Tasks summarizes user research, then presents design sketches of systems that illustrate how design is linked to research. Also discussed are usable information services and an overview of the organizationand economics of information institutions. This comprehensive user-centered approach provides an agenda for information research, design, and education that challenges many accepted beliefs and suggests new directions for information work. Information Tasks will be of interest to library and information science students and faculty interested in information storage
and retrieval, user studies, and systems analysis design. Students and scholars of human factors in systems design, humanÐcomputer interaction, and cognitive engineering will also find the text useful.

Brown, M. E. and J. J. Gallimore (1995). "Visualization of three-dimensional structure during computer-aided design." International Journal of Human Computer Interaction 7(1): 37-56
[Interface Design, Structural Integrity: Depth Cues].

Examined the effects of stereopsis on ability to (1) accurately transfer to, and retrieve from, long-term memory spatial information about 3-D objects; and (2) visualize spatial characteristics quickly and directly. Ss memorized the shape of a 3-D object presented on a stereoscopic CRT and were then shown a series of static trial stimuli. Ss were to determine whether the trial object was the same shape as the memorized object or its mirrored image. To assess the merits associated with disparity and interposition, 2 depth cues were manipulated in a within-S design during the study and trial periods. Results showed improved performance due to hidden surface. Results also revealed a significant effect of stereopsis. Under specific study object conditions, adding disparity to monocular trial objects significantly decreased response time. Response latency was also decreased by adding disparity information to stimuli in the study session. (PsycLIT Database Copyright 1996 American Psychological Assn, all rights reserved)

Card, S. K., P. Moran and A. Newell (1980). The Psychology of Human-Computer Interaction. Hillsdale, NJ, Lawrence Ealbaum Associates
[Interface Design].

This seminal work provides a framework for an engineering psychology approach to HCI. It outlines detailed mechanisms for testing the GOMS model at several levels. Case studies are included.

Carswell, C. M. (1992). "Choosing specifiers: An evaluation of the basic tasks model of graphical perception. Special Issue: Visual displays." Human Factors **34**(5): 535-554
[Interface Design, Evaluation].

Used effect sizes from 39 experiments to evaluate the predictions of the basic tasks model of graphical efficacy. This model predicts that performance will be attenuated with graphical displays as a function of the particular specifier used to code data values. In this review the basic tasks model predicted performance more accurately than did E. R. Tufte's (1983, 1990) data-ink principle. In addition, variability in effect size across studies revealed that the model was more successful at predicting performance in local tasks than in global information synthesis tasks, as well as in tasks requiring the use of physically present rather than remembered graphs. Minimal differences were obtained among graphs that used position, length, or angle as specifiers. However, graphs that used area or volume to represent quantitative values were associated with consistently worse performance than found with other formats. (PsycLIT Database Copyright 1993 American Psychological Assn, all rights reserved)

Cleveland, W. S., C. S. Harris and R. McGill (1983). "Experiments on quantitative judgments of graphs and maps." Bell System Technical Journal **62**(6, Pt 3): 1659-1674
[Interface Design]

Conducted 3 experiments on reading graphs and maps. In Exp I, 24 employees of Bell Laboratories viewed a map on which half of the geographical areas were red and half were green. Ss tended to perceive more red areas than green areas. In Exp II, 14 scientists read a maplike display of circles that represented telephone charges. It was found that Ss had widely varying impressions of the compensatory scaling of area. 10 high school students showed similar responses. In Exp III, 109 Ss viewed a scatter plot and indicated the degree of association of 2 variables. Estimated association was higher for the smaller point cloud than for the larger one. Results were corroborated with 32 other Ss and detailed with 74 Ss. Recommendations include the following: (1) Use pastel rather than highly saturated colors on statistical maps; (2) standardize the point cloud size relative to the frame on the scatter plot; and (3) scale circles by making circle area proportional to the variable represented but expect widely varying judgments of the areas. (21 ref) (PsycLIT Database Copyright 1984 American Psychological Assn, all rights reserved)

Cleveland, W. S. and R. McGill (1986). "An experiment in graphical perception." International Journal of Man Machine Studies **25**(5): 491-500
[Interface Design].

Investigated the accuracy of 6 basic judgments of graphical perception, using 24 high school students, 60 college students, and 43 technically trained professionals. Ss judged 7 types of stimuli requiring judgments of (1) position along a common scale, (2) position along identical nonaligned scales, (3) length, (4) slope, (5) angle, (6) area of circles, and (7) area of blobs. 2 types of position judgments were the most accurate, length judgments were 2nd, angle and slope judgments were 3rd, and area judgments were last. Distance between judged objects was a factor in the accuracy of the basic judgments, but level of technical training of Ss did not affect accuracy. (PsycLIT Database Copyright 1987 American Psychological Assn, all rights reserved)

Colet, E. and D. Aaronson (1995). "Visualization of multivariate data: Human-factors considerations." 24th Annual Meeting of the Society for Computers in Psychology (1994, St Louis, Missouri). Behavior Research Methods, Instruments and Computers **27**(2): 257-263
[Interface Design].

Recent software provides new tools for visualizing multivariate data that facilitate data analysis. This article focuses on the learnability and use of visualization systems, and the perceptual and cognitive processes involved in viewing visualizations. Effective visualization systems support a broad range of user tasks and abilities, are easy to learn, and provide powerful and flexible output formatting. The human factors perspective outlined here maintains that effective visualizations incorporate Gestalt and other perceptual and cognitive principles that encourage more rapid, automatic processing, and less slow, controlled processing.

Davis, E. T., G. M. Corso, W. Barfield, R. G. Eggleston, S. Ellis, B. Ribarsky and C. D. Wickens (1994). Human Perception and Performance in 3D Virtual Environments. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 230-234
[Interface Design].

Virtual environments have the potential to become very significant tools both in the civilian and military sectors. They offer a new human-computer interface in which users actively participate and are totally immersed in a computer-generated 3D virtual world. Important applications of virtual environments include the scientific visualization of complex data sets, the operation of remotely manipulated vehicles or teleoperators, the display of aircraft locations for air traffic control, simulated flight training, simulated driving training, teleoperated surgery as well as medical training and skill acquisition in surgery. Because virtual environments offer greater flexibility than most traditional HCI interfaces, those and other tasks may be better handled by virtual environments than by more traditional HCI interfaces. For example, virtual reality technology offers the capability of 3D or 2D representations, egocentric or exocentric 3D viewpoint, stereoscopic or monoscopic views, dynamically changing or relatively static representations as well as the availability of multi-sensory information (e.g., visual, auditory, and tactile inputs) and of perceptual-motor interactions. Yet, current VR systems still suffer from technical limitations that may restrict their usefulness. These technical limitations include poor spatio-temporal resolution of visual, auditory, and haptic images; cross-sensory image registration; and inaccuracy of head and eye tracking devices. Some of these limitations may be overcome by advances in the technology while other limitations may be overcome by cleverly adapting the VE system to exploit the capabilities and limitations of human perception. In all applications of virtual environments, human spatial perception plays a crucial role. For example, distance, elevation, and azimuth information is used to determine where objects are located. Yet, the perceived spatial location of an object may be ambiguous within a given display. Stereoscopic displays can provide humans with visual cues to disambiguate this information. But, there are other ways to resolve this ambiguity, such as the use of other visual cues or of other sensory modalities (e.g., auditory and haptic senses). Moreover, determination of the "best" perceptual cues and the "best" sensory modalities may be task dependent.

Gillan, D. J. and E. H. Richman (1994). "Minimalism and the syntax of graphs." Human Factors **36**(4): 619-644
[Interface Design].

Examined E. R. Tufte's (1983) syntactic rule that graphs should have maximal data-ink ratios produced by erasing non-data-ink and redundant data-ink in 4 experiments consisting of 17 undergraduates in each experiment. Exp 1 examined the data-ink ratios of bar and line graphs and their effects on accuracy and response times. Results showed that an increase on the data-ink ratio benefitted speed and accuracy. Exps 2, 3A, and 3B investigated the effects of ink on the syntactic elements of a graph based on the function and location of the element. Results indicated that ink can be helpful or detrimental to the graph reader depending on the function and location of the ink, the user's task, type of graph, and the physical relations among graphical elements. The discussion focuses on psychological principles of human graph interaction and those underlying the effects of each syntactic element. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

Masui, T., M. Minakuchi, I. V. George R. Borden and K. Kashiwagi (1995). Multiple-View Approach for Smooth Information Retrieval. Proceedings of the ACM Symposium on User Interface Software and Technology 199-206
[Interface Design, Sequential Clarity: Navigation].

Although various visualization techniques have been proposed for information retrieval tasks, most of them are based on a single strategy for viewing and navigating through the information space, and vague knowledge such as a fragment of the name of the object is not effective for the search. In contrast, people usually look for things using various vague clues simultaneously. For example, in a library, people can not only walk through the shelves to find a book they have in mind, but also they can be reminded of the author's name by viewing the books on the shelf and check the index cards to get more information. To enable such realistic search strategies, we developed a multiple-view information retrieval system where data visualization, keyword search, and category search are integrated with the same smooth zooming interface, and any vague knowledge about the data can be utilized to narrow the search space. Users can navigate through the information space at will, by modifying the search area in each view.

Murray, B. S. and E. McDaid (1993). “Visualizing and Representing Knowledge for the End User: A Review.” International Journal of Man-Machine Studies **38**(1): 23-49
[Interface Design].

The field of visualization and its various aspects are discussed. Visual programming and program visualization are discussed, with particular reference to visual programming languages. A collection of recent systems taken from the scientific literature are then described. The factors of particular importance to the development of such systems are briefly mentioned. The outstanding areas for research are discussed with the finding of suitable graphical representations being seen as particularly important.

Rasmussen, J., Pejtersen, Annelise, & Goodstein, L.P (1994). Cognitive Systems Engineering. New York, Wiley
[Interface Design].

This book extends the conceptual foundations regarding human information processing and human-system interaction presented in an earlier book by the first author. It attempts to illustrate how cognitive theory can contribute to application. Several examples are developed in some detail.

Schneiderman , B. (1997). Designing the User Interface : Strategies for Effective Human-Computer Interaction. Reading, MA, Addison-Wesley Pub Co
[Interface Design].

In this revised and updated presentation of user interface design for designers, managers, and evaluators of interactive systems, Schneiderman discusses the underlying issues, principles, and empirical results, and describes practical guidelines and techniques necessary to realize an effective design.

Sebrechts, M. M., B. A. Knott and M. P. Etgen (1997). Human-Computer Interaction Guidelines for Images Exploitation Systems. Washington, DC, The National Imagery and Mapping Agency. [Interface Design].

This document contains Human-Computer Interaction guidelines which are part of a principled approach to design. This appraoch assumes that design should be based on the theory and research in human cognition as it relates to HCI. The report combines results from academic and industrial research with more task specific studies from the National Exploitation Laboratory. Although the report includes materials specific to current imagery analysis, it is future oriented in that it also covers more general issues that may be relevant in as yet unspecified implementations.

Spence, I. and S. Lewandowsky (1991). "Displaying proportions and percentages." Applied Cognitive Psychology **5**(1): 61-77
[Interface Design].

Four experiments contrasted pie charts, bar charts, and tables that are commonly used to display proportional and percentage data. 41 Ss from a university community performed tasks that ranged from simple comparisons to more complicated ones involving pairs of components. The pie chart compared favorably with the bar chart when tasks other than direct magnitude estimation were required. When making comparisons of combinations of proportions, the pie chart enjoyed an advantage. Moreover, unless the object was to transmit precise numerical values of proportions or percentages to the reader, tables appeared to be inferior to charts as display devices. The use of color seemed to be beneficial. (PsycLIT Database Copyright 1991 American Psychological Assn, all rights reserved)

Tufte, E. (1989). The Visual Display of Quantitative Information. Chesire, CT, Graphics Press
[Interface Design].

I GRAPHICAL PRACTICE
1 Graphical Excellence
2 Graphical Integrity
3 Source of Graphical Integrity and Sophistication
II THEORY OF DATA GRAPHICS
4 Data-Ink and Graphical Redesign
5 Chartjunk: Vibrations, Grids, and Ducks
6 Data-Ink Maximization and Graphical Design
7 Multifunctioning Graphical Elements
8 Data Density and Small Multiples
9 Aesthetics and Technique in Data Graphical Design
Epilogue: Designs for the Display of Information

Tufte, E. R. (1990). Envisioning information. Cheshire, CT, Graphics Press
[Interface Design].

(from the introduction) The world is complex, dynamic, multidimensional; the paper is static, flat. How are we to represent the rich visual world of experience and measurement on mere flatland? /// This book celebrates escapes from flatland, rendering several hundred superb displays of complex data. Revealed here are design strategies for enhancing the dimensionality and density of portrayals of information--techniques exemplified in maps, the manuscripts of Galileo, timetables, notation describing dance movements, aerial photographs, the Vietnam Veterans Memorial, electrocardiograms, drawings of Calder and Klee, computer visualizations, and a textbook of Euclid's geometry. /// Our investigation yields general principles that have specific visual consequences, governing the design, editing, analysis, and critique of data representations. These principles help to identify and to explain design excellence--why some displays are better than others. Charts, diagrams, graphs, tables, guides, instructions, directories, and maps comprise an enormous accumulation of material. Once described by Philip Morrison as "cognitive art," it embodies tens of trillions of images created and multiplied the world over every year. Despite the beauty and utility of the best work, design of information has engaged little critical or aesthetic notice: there is no Museum of Cognitive Art. This book could serve as a partial catalog for such a collection.

Tufte, E. R. (1997). Visual Explanations: Images and Quantities, Evidence and Narrative. Cheshire, CT, Graphics Press
[Interface Design].

"Visual Explanations" is Tufte's third in a series of books on preparing effective visual media. While his first, The Display of Quantitative Explanation (1983), is about depiction of numbers, and his second, Envisioning Information (1990), is about pictures of nouns (e.g. maps), this volume focuses on pictures of verbs . For example, the chapter on "Images and Quantities" describes visual techniques for depicting quantity and time evolution. The chapter on "Visual and Statistical Thinking" provides examples of how effective graphical display of statistical information supports critical decision making. While emphasis is placed on guidelines for printed media and electronic publication, a number of examples of human-computer interface design are included in this volume.

Wann, J. and M. Mon-Williams (1996). "What Does Virtual Reality NEED?: Human Factors Issues in the Design of Three-Dimensional Computer Environments." International Journal of Human-Computer Studies **44**(6): 829-847
[Interface Design, Identifiability: Perceptual Grouping, Sequential Clarity: Navigation, Familiarity].

Virtual reality (VR) has invaded the public's awareness through a series of media articles that have promoted it as a new and exciting form of computer interaction. We discuss the extent to which VR may be a useful tool in visualization and attempt to disambiguate the use of VR as a general descriptor for any three-dimensional computer presentation. The argument is presented that, to warrant the use of the term virtual environment (VE), the display should satisfy criteria that arise from the nature of human spatial perception. It directly follows, therefore, that perceptual criteria are the foundations of an effective VE display. We address the task of making a VE system easy to navigate, traverse and engage, by examining the ways in which three-dimensional perception and perception of motion may be supported, and consider the potential conflict that may arise between depth cues. We propose that the design of VE systems must centre on the perceptual-motor capabilities of the user, in the context of the task to be undertaken, and establish what is essential, desirable and optimal in order to maximize the task gains, while minimizing the learning required to operate within three-dimensional interactive displays.

Yu, C. H. and J. T. Behrens (1995). "Applications of multivariate visualization to behavioral sciences. 24th Annual Meeting of the Society for Computers in Psychology (1994, St Louis, Missouri)." Behavior Research Methods, Instruments and Computers **27**(2): 264-271 [Interface Design].

Defines scientific visualization as the process of exploring and displaying data in a manner that builds a visual analogy to the physical world in the service of user insight and learning. The framework for understanding statistical graphics that is outlined here is based on the idea of balance in depicting detail as opposed to summarizing when one is constructing summaries that are either local or global. The process of visualization can be viewed as an adjustment of noise and smooth . Visualization methods for multivariate data discussed here include stereo-ray glyphs, volume model, surface plot, contour plot, image plot, coplot, scatterplot matrix brushing, and animated mesh surface.

III. Design Principles

A. Perceiving and Evaluating the System: Make it easy for the user to perceive and evaluate the structure and state of the system.

A.1. Visibility: Make the state of the system, available interactions, and consequences of user action readily apparent, minimizing the need for the user to remember or infer information.

Bennett, K. B. (1993). "Encoding apparent motion in animated mimic displays." Human Factors **35**(4): 673-691
[Visibility].

Display variables likely to influence the effectiveness of apparent motion were investigated in 2 experiments using 11 observers. The primary experimental manipulations were the levels of chromatic and luminance contrast in the displays (temporal frequency and direction of apparent motion were also varied). Results suggest that both types of contrast can be used to encode apparent motion but that luminance contrast is more effective. Additional variables likely to influence the effectiveness of animation (e.g., wave form, spatial and temporal frequency, orientation, and shape) that were held constant in these experiments were discussed. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

Calhoun, G. L., W. P. Janson and G. Valencia (1988). Effectiveness of Three-Dimensional Auditory Directional Cues. Proceedings of the Human Factors Society 32nd Annual Meeting 68-72
[Visibility].

Natural aural directional cueing in the cockpit should relieve the demands placed on the visual modality, reduce display clutter and alleviate cognitive attention needed to process and extract meaning from coded formats. This experiment compared the effectiveness of three-dimensional (3-D) auditory cues to conventional visual and auditory methods of directing visual attention to peripheral targets. Five directional cues were evaluated: visual symbols, coded aural tone, speech cue, 3-D tone (white noise appearing to emanate from peripheral locations) and 3-D speech (speech cue appearing to emanate from peripheral locations). The results showed significant performance differences as a function of directional cue type in peripheral target task completion time, as well as eye and head reaction time. Results, such as these, will help improve the application of directional sound in operational cockpits.

Jerding, D. F. and J. T. Stasko (1995). Using Information Murals in Visualization Applications, Proceedings of the ACM Symposium on User Interface Software and Technology 73-74
[Visibility].

Information visualizations must allow users to browse information spaces and focus quickly on items of interest. Navigational techniques which utilize some representation of the entire information space provide context to support more detailed information views. However, the limited number of pixels on the screen makes it difficult to completely display large information spaces. The Information Mural is a two-dimensional, reduced representation of an entire information space that fits entirely within a display window or screen. The mural creates a miniature version of the information space using visual attributes such as grayscale shading, intensity, color, and pixel size, along with anti-aliased compression techniques. Information murals can be used as stand-alone visualizations or in global navigational views.

Koike, H. (1995). "Fractal Views: A Fractal-Based Method for Controlling Information Display." ACM Transactions on Information Systems **13**(3): 305-323
[Visibility, Example].

Computer users often must view large amounts of information through video displays which are physically limited in size. Although some methods, which automatically display/erase information units based on their degrees of importance, have been proposed, they lack an ability to keep the total amount of displayed information nearly constant. We propose a new method for information display based on fractal theory. By regarding the information structures used in computers as complex objects, we can abstract these objects as well as control their amount. Using our method, (1) the total amount of information is kept nearly constant even when users change their focuses of attention and (2) this amount can be set flexibly. Through mathematical analysis, we show our method's ability to control the amount. An application to program display is also shown. When this method is applied to the display of structured programs, it provides fisheye-like views which integrate local details around the focal point and major landmarks further away.

Leinonen, L., T. Hiltunen, K. Torkkola and J. Kangas (1993). "Self-organized acoustic feature map in detection of fricative-vowel coarticulation." Journal of the Acoustical Society of America **93**(6): 3468-3474
[Visibility].

Samples of (s) preceding (a), (i), or (u), obtained from 13 20-50 yr old women, were studied with a feature map computed from the speech samples of 19 women. The map results were compared with the psychoacoustic classification of the same data. Results demonstrate that the self-organizing map clusters speech spectra in a perceptually meaningful way and provides an understandable on-line visualization of speech sounds.

Mackinlay, J. D., G. G. Robertson and S. K. Card (1991). The Perspective Wall: Detail and Context Smoothly Integrated. Proceedings of ACM CHI'91 Conference on Human Factors in Computing Systems 173-179
[Visibility].

Tasks that involve large information spaces overwhelm workspaces that do not support efficient use of space and time. For example, case studies indicate that information often contains linear components, which can result in 2D layouts with wide, inefficient aspect ratios. This paper describes a technique called the Perspective Wall for visualizing linear information by smoothly integrating detailed and contextual views. It uses hardware support for 3D interactive animation to fold wide 2D layouts into intuitive 3D visualizations that have a center panel for detail and two perspective panels for context. The resulting visualization supports efficient use of space and time.

Smith, S., R. D. Bergeron and G. G. Grinstein (1990). Stereophonic and Surface Sound Generation for Exploratory Data Analysis. Proceedings of ACM CHI'90 Conference on Human Factors in Computing Systems 125-132

[Visibility].

The analysis and interpretation of very high dimensional data require the development and use of data presentation techniques that harness human perceptual powers. The University of Lowell's Exploratory Visualization project (Exvis) aims at designing, implementing, and evaluating perceptually-based tools for data presentation using both visual and auditory domains. This paper describes several auditory data presentation techniques, including the generation of stereophonic sound with apparent depth and sound that appears to emanate from a two-dimensional area. Both approaches can produce sound with auditory texture.

Wenzel, E. M., F. L. Wightman and D. J. Kistler (1991). Localization with Non-Individualized Virtual Acoustic Display Cues. Proceedings of ACM CHI'91 Conference on Human Factors in Computing Systems 351-359
[Visibility].

A recent development in advanced interface technologies is the virtual acoustic display, a system that presents three-dimensional auditory information over headphones. The utility of such a display depends on the accuracy with which listeners can localize the virtual, or simulated, sound sources. Synthesis of virtual sources involves the digital filtering of stimuli using filters based on acoustic Head-Related Transfer Functions (HRTFs) measured in human ear-canals. In practise, measurement of the HRTFs of each potential user of a 3-D display may not be feasible. Thus, a critical research question is whether listeners from the general population can obtain adequate localization cues stimuli based on non-individualized filters. In the present study, 16 inexperienced listeners judged the apparent spatial location (azimuth and elevation) of wideband noisebursts that were presented either over loudspeakers in the free-field (an anechoic or non-reverberent environment) or over headphones. The headphone stimuli were synthesized using HRTFs from a representative subject in a previous study. Localization of both free-field and virtual sources was quite accurate for 12 of the subjects, 2 showed poor elevation accuracy in both free-field and headphone conditions, and 2 showed degraded elevation accuracy only with virtual sources. High rates of confusion errors (reversals in judgements of azimuth and elevation) were also observed for some of the subjects and tended to increase for the virtual sources. In general, the data suggest that most listeners can obtain useful directional information from an auditory display without requiring the use of individually-tailored HRTFs, particularly for the dimension of azimuth. However, the high rates of confusion errors remain problematic. Several stimulus characteristics which may help to minimize these errors are discussed.

Wickens, C. D. and J. Long (1995). “Object versus space-based models of visual attention: Implications for the design of head-up displays.” Journal of Experimental Psychology Applied **1**(3): 179-193
[Visibility].

Thirty-two pilots flew instrument approaches in a high-fidelity simulator, first inside and then outside of the clouds. They used 2 symbology sets, presenting flight guidance information that was either conformal or nonconformal with the background. Half of the trials presented the symbology in a head-up location, and half presented the symbology head-down. Airspeed tracking was displayed with nonconformal digital symbology. An unexpected far domain event was presented on 1 trial per pilot. For flightpath control, there was a benefit for head-up location for conformal, but not for nonconformal symbology. The head-up display viewed over the background eliminated advantages to tracking airspeed and nonconformal symbology that had been present while in the clouds. Head-up display also produced a slower response to the far domain unexpected event. The results are interpreted within the theoretical framework of object-based and space-based theories of visual attention, and the tradeoffs between clutter of overlapping imagery and information access cost. These are incorporated in a processing model that can guide the appropriate choice of symbology for head-up displays.

A.2. Identifiability: Make the meaning of an object or statement clear and distinct from other objects or statements.

Boker, S. M. and J. J. McArdle (1995). "Statistical vector field analysis applied to mixed cross-sectional and longitudinal data." Experimental Aging Research **21**(1): 77-93 [Identifiability, Structural Integrity].

Presents a method by which cross sectional and longitudinal data can be visualized, along with several examples from a data set comprising measurements of intellectual abilities with respect to aging. This method is called a statistical vector field (SVF) plot. An SVF plot simultaneously allows the visualization of cross-sectional information summarizing sampling densities and longitudinal information summarizing how individuals at each particular age and ability are likely to change over time.

Wickens, C. D. and C. M. Carswell (1995). "The proximity compatibility principle: Its psychological foundation and relevance to display design." Human Factors **37**(3): 473-494 [Cognition and Perception, Visibility, Identifiability].

Describes the proximity compatibility principle (PCP) and its relevance to display design. Displays relevant to a common task or mental operation (close task or mental proximity) should be rendered close together in perceptual space (close display proximity). Different forms of task proximity are discussed, as are the different information-processing mechanisms that underlie the effects of the several different design manipulations of display proximity. Experimental data that support this process-based elaboration of PCP are reviewed in design contexts relating to aviation, graphs, display layout, and decision aiding.

Dimensionality

Abed, F. (1991). "The influence of dimensionality on eye fixations." Perception **20**(4): 449-454 [Identifiability: Dimensionality].

Eye fixation patterns were explored for 60 graduate students, each of whom viewed 1 of 3 stimuli, either in a 3-dimensional (3-D) model format or in a 2-dimensional (2-D) photographic format. The stimuli consisted of 1 symmetrical and 2 asymmetrical color representational drawings displayed in the form of a photograph or of a model. Total fixation times (in msec) were computed for 7 portions of each stimulus: top, bottom, left, right, foreground, middle ground, and background. Results indicate that for all stimuli, Ss viewing the 3-D model spent significantly more time fixating the foreground and significantly less time fixating the background than Ss viewing the 2-D photograph. For the 2 asymmetrical stimuli, Ss in the 2 groups differed significantly in their fixation patterns for the left/right variables. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Barfield, W. and R. Robless (1989). "The effects of two- or three-dimensional graphics on the problem-solving performance of experienced and novice decision makers." Behaviour and Information Technology **8**(5): 369-385
[Identifiability: Dimensionality, Diversity].

Investigated the relationship between 2-dimensional (2-D) or 3-dimensional (3-D) graphs displayed on paper or computer and the problem-solving performance of experienced (EMs) and novice managers (NMs). 33 graduate engineering management students (NMs) and EMs and engineers solved 1 case study for each of 4 modes of information presentation. Verbal protocols and retrospective reports indicated that in solving the cases, EMs engaged in forward chaining, backward chaining, and means-end analysis as problem-solving techniques more often than did NMs. EMs produced more accurate answers with 3-D graphs on computer, whereas NMs did better with 2-D graphs on paper. All Ss were more confident using 2-D graphs. (PsycLIT Database Copyright 1990 American Psychological Assn, all rights reserved)

Brown, M. H. and M. A. Najork (1993). Algorithm Animation using 3D Interactive Graphics. Proceedings of the ACM SIGGRAPH Symposium on User Interface Software and Technology 93-100
[Visibility, Identifiability: Dimensionality].

This paper describes a variety of 3D interactive graphics techniques for visualizing programs. The third dimension provides an extra degree of freedom for conveying information, much as color adds to black-and-white images, animation adds to static images, and sound adds to silent animations. The examples in this paper illustrate three fundamental uses of 3D: for providing additional information about objects that are intrinsically two-dimensional, for uniting multiple views, and for capturing a history of execution. The application of dynamic three-dimensional graphics to program visualization is largely unexplored.

Bullemer, P. T., S. V. Metz and R. M. Richardson (1992). A User Interface Design Concept for Visualization of Multidimensional Process Models. Proceedings of the Human Factors Society 36th Annual Meeting 361-364
[Identifiability: Dimensionality, Visibility, Preference].

A user interface design concept for the interactive visualization of multidimensional industrial process models is described. Key features of the design include: a matrix layout of 3-D and 2-D graphical plots, an interaction area for visualizing integral relationships and selecting context for viewing individual x-y functions, and a reference area extending throughout the matrix for maintaining focus on desirable values of product quality. These features are motivated by task-specific needs to develop conceptual models of the physical processes used in making products. Conceptual models enable process engineers to determine the optimal operating ranges for controllable process parameters.

Carswell, C. M., S. Frankenberger and D. Bernhard (1991). “Graphing in depth: Perspectives on the use of three-dimensional graphs to represent lower-dimensional data.” Behaviour and Information Technology **10**(6): 459-474
[Identifiability: Dimensionality].

Evaluated performance on such graphical formats as line graphs (LGs), bar charts (BCs), and pie charts constructed with and without the 3-dimensional (3D) look. 122 university students participated in 3 experiments. When Ss were asked to make relative magnitude estimations, only the 3D LGs resulted in reliable performance decrements. Likewise, information presented in 3D LGs was remembered less accurately than information presented in 2D LGs. For the estimation of global trends, both 3D LGs and BCs were used more quickly than 2D formats, but this speed was obtained at the expense of accuracy. For a trend classification task involving more focused processing, 3D LGs and BCs were associated with an overall performance decrement when compared with their 2D counterparts. The use of 3D designs may also influence the attitudes formed by Ss toward the information presented in the graphs. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

Chang, B.-W. and D. Ungar (1993). Animation: From Cartoons to the User Interface. Proceedings of the ACM SIGGRAPH Symposium on User Interface Software and Technology 45-55
[Identifiability: Dimensionality].

User interfaces are often based on static presentations, a model ill suited for conveying change. Consequently, events on the screen frequently startle and confuse users. Cartoon animation, in contrast, is exceedingly successful at engaging its audience; even the most bizarre events are easily comprehended. The Self user interface has served as a testbed for the application of cartoon animation techniques as a means of making the interface easier to understand and more pleasant to use. Attention to timing and transient detail allows Self objects to move solidly. Use of cartoon-style motion blur allows Self objects to move quickly and still maintain their comprehensibility. Self objects arrive and depart smoothly, without sudden materializations and disappearances, and they rise to the front of overlapping objects smoothly through the use of dissolve. Anticipating motion with a small contrary motion and pacing the middle of transitions faster than the endpoints results in smoother and cleared movements. Despite the differences between user interfaces and cartoons -- cartoons are frivolous, passive entertainment and user interfaces are serious, interactive tools -- cartoon animation has much to lend to user interfaces to realize both affective and cognitive benefits.

Eick, S. G. (1994). Data Visualization Sliders. Proceedings of the ACM Symposium on User Interface Software and Technology 119-120
[Identifiability: Dimensionality, Example].

Computer sliders are a generic user input mechanism for specifying a numeric value from a range. For data visualization, the effectiveness of sliders may be increased by using the space inside the slider as an interactive color scale, a barplot for discrete data, and a density plot for continuous data. The idea is to show the selected values in relation to the data and its distribution. Furthermore, the selection mechanism may be generalized using a painting metaphor to specify arbitrary, disconnected intervals while maintaining an intuitive user-interface.

Goettl, B. P., C. D. Wickens and A. F. Kramer (1991). "Integrated displays and the perception of graphical data. Special Issue: Cognitive ergonomics II." Ergonomics **34**(8): 1047-1063
[Identifiability: Dimensionality, Structural Integrity, Situation].

Three experiments (N = 91 university students) applied a principle of compatibility of proximity to perception of graphical data. Results demonstrate that merits and costs of integral displays relative to separable displays depend in part on the task being performed. Exp 1 employed a data extrapolation task in which information had to be integrated. Here an integral display was superior to a separable display. Exp 2 employed a data perception task that required focused attention, revealing superior performance with separable displays. Exp 3 employed a multiple cue judgment task in which information integration could be manipulated and indicated that knowledge of task structure was influenced by display type. When selective attention was required, knowledge of the task was superior with separable displays.

Habibi, S. K. and D. S. Ranson (1993). Visualizing Multidimensional Process Control Relationships. Proceedings of the Fifth International Conference on Human-Computer Interaction 555-560
[Identifiability: Dimensionality].

A case study has been performed to develop function-based displays to support power plant operators controlling component stress in a set of steam generators during heat-up and cool-down manoeuvres. Based on a function and task analysis, a set of displays has been developed to show the multidimensional relationship between the process parameters and to support the operators in detection, diagnosis, prediction, and incident recovery. Display options include 2D and 3D graphic representations. It has been concluded that 2D graphic displays are more effective than 3D displays for representing the multidimensional relationships. Further, displays have been developed to allow operators to predict the effects of changes in controllable variables on the key parameters that impact component stress.

Haskell, I. D. and C. D. Wickens (1993). "Two- and three-dimensional displays for aviation: A theoretical and empirical comparison." International Journal of Aviation Psychology **3**(2): 87-109
[Identifiability: Dimensionality, Structural Integrity, Situation].

Examined the trade-offs in using 2- and 3-dimensional perspective displays for aviation as predicted by C. D. Wickens and A. D. Andre's (see PA, Vol 77:30080) proximity compatibility principle. One display incorporated 3 orthogonal spatial views, and the other a single, 3-dimensional, inside-out perspective view. 20 pilots performed tasks on 1 of the 2 displays. Performance measures included (1) flight-path tracking accuracy during routine flight and during loss of situational awareness, (2) accuracies and response times for 3 judgment events, (3) the incidence of integrated control actions in several dimensions, and (4) subjective workload ratings. The 3-dimensional perspective display fostered superior lateral and altitude flight-path tracking accuracy, whereas the 2-dimensional display fostered superior airspeed tracking accuracy.

Hastie, R., O. Hammerle, J. Kerwin and D. J. Hermann (1996). "Human performance reading statistical maps." Journal of Experimental Psychology Applied **2**(1): 3-16 [Identifiability: Dimensionality].

Three experiments were conducted to explore the conditions under which certain map formats would most effectively represent certain types of statistical information. The major practical finding was that multiple-hue formats convey either numerical or categorical information more efficiently than ordered monochrome brightness-varying formats when the task is to identify data values for single map locations. However, the advantage of the multiple-hue formats was eliminated when more complex tasks were performed. These included tasks such as integrating values from several locations to estimate an average for a region. The researchers concluded from these studies that the nature of the reader's task when selecting a format is at least as important a consideration as the nature of information represented in the map. (PsycLIT Database Copyright 1996 American Psychological Assn, all rights reserved)

Herndon, K. P. and T. Meyer (1994). 3D Widgets for Exploratory Scientific Visualization. Proceedings of the ACM Symposium on User Interface Software and Technology 69-70 [Identifiability: Dimensionality].

Scientists use a variety of visualization techniques to help understand computational fluid dynamics (CFD) datasets, but the interfaces to these techniques are generally two-dimensional and therefore separated from the 3D view. Both rapid interactive exploration of datasets and precise control over the parameters and placement of visualization techniques are required to understand complex phenomena contained in these datasets. In this paper, we present work in progress on a 3D user interface for exploratory visualization of these datasets.

Jones, S. (1993). 3-D Diagrams for Knowledge Engineering: An Early Estimation of Utility. Proceedings of the Fifth International Conference on Human-Computer Interaction 561-566 [Identifiability: Dimensionality, Identifiability: Perceptual Grouping].

The utility of 3-d diagrams for knowledge engineering was evaluated in six case studies. Knowledge engineers were asked to collaborate in the design of 3-d diagrammatic representations of knowledge structures. The knowledge engineers then carried out a series of simple tasks using these representations. Performance in these tasks was observed and think aloud protocols were recorded. Structured interviews were also used to elicit the opinions of the knowledge engineers regarding the utility of 3-d diagrammatic representations in their normal working practices. It was judged that 3-d diagrams are likely to be more useful than 2-d in the development of object or frame-based (rather than rule-based) systems. Engineers predicted that 3-d would be more useful than 2-d in design and debugging tasks, but that the advantage in knowledge acquisition, validation, verification and maintenance would not be as great. It was noted that the utility of 3-d diagrams need not be severely limited either by the need for specialised hardware, or by variations in user experience. It is concluded that future tools for knowledge engineering could benefit from the inclusion of a 3-d interface component. Tools supporting the development of conventional systems, in which various kinds of relationship between system objects are used in design and development, might also benefit in the same way.

Jones, W. P. and S. T. Dumais (1986). "The Spatial Metaphor for User Interfaces: Experimental Tests of Reference by Location versus Name." ACM Transactions on Office Information Systems **4**(1): 42-63
[Identifiability: Dimensionality].

The enduring dichotomy between spatial and symbolic modes of representation and retrieval acquires an added pragmatic dimension through recent developments in computer-based information retrieval. The standard name-based approach to object reference is now supplemented on some systems by a spatial alternative-often driven by an office or desktop metaphor. Little rigorous evidence is available, however, to support the supposition that spatial memory in itself is more effective than symbolic memory. experiments. In Experiment 1 accuracy of location reference in a location-only filing condition was initially comparable to that in a name-only condition, but deteriorated much more rapidly with increases in the number of objects filled. In Experiment 2 subjects placed objects in a two-dimensional space containing landmarks (drawings of a desk, table, filing cabinets, etc.) designed to evoke an office metaphor, and in Experiment 3 subjects placed objects in an actual, three-dimensional mock office. Neither of these enhancements served to improve significantly the accuracy of location reference, and performance remained below that of a name-only condition in Experiment 1. The results raise questions about the utility of spatial metaphor over symbolic filing and highlight the need for continuing research in which considerations of technological and economic feasibility are balanced by considerations of psychological utility.

Marchak, F. M. (1994). "An overview of scientific visualization techniques applied to experimental psychology." Behavior Research Methods, Instruments and Computers **26**(2): 177-180
[Identifiability: Dimensionality].

Presents an overview of current data visualization techniques. The various types of graphics, such as contour plots, scatterplot matrices, and dynamic spinning are described. Using a data set typical of the field (similarity judgments), the potential merits and pitfalls of each visualization technique are presented in terms of what aspects of the data they make explicit. Results illustrate the benefits that a psychological researcher can expect from data visualization capabilities.

Merwin, D. H. and C. D. Wickens (1991). 2-D vs. 3-D Display for Multidimensional Data Visualization: The Relationship Between Task Integrality and Display Proximity. Proceedings of the Human Factors Society 35th Annual Meeting 388-392
[Identifiability: Dimensionality].

The current study explores the relationship between the display representation of a multidimensional data base (separated vs. integrated) and the information processing demands of different types of tasks. Subjects answered a range of questions about a complex economic data base while viewing either a 2-D or 3-D (perspective) display of subsets of the data. Animated vs. static representations of dynamic data were also examined. The 3-D display supported better performance than did the 2-D display on the more integrative questions, while no difference between formats was found for questions demanding focused attention. The 3-D display also supported a better visual model of the data space, but did not improve subjects' ability to verbalize the rules underlying this space. Animation did not provide a better means for understanding change information than did the static presentation mode. Implications for the design of data visualization display interfaces are discussed.

Mullet, K., D. L. Schiano, G. Robertson, J. Tesler, B. Tversky, K. Mullet and D. J. Schiano (1995). 3D or Not 3d: "More is Better" or "Less is More"? Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 174-175
[Identifiability: Dimensionality].

The rapid growth in platform-level support for real-time 3D rendering and animation has recently created an explosion of public interest in adding to the dimensionality of the user interface, and the SIGCHI community has been a major source of activity in this area. This panel considers several points of view on the ever-increasing use of 3D visual representations in the user interface itself. We aim to help distinguish between conditions under which "more" truly is better -- from a user-centered perspective -- and those in which a well-designed 2D solution would serve as well or even better. Panelists will offer examples of applications in which 3D is highly essential or completely unnecessary.

Steinberg, D., C. DePlachett, K. Pathak and D. Strickland (1995). 3-D Displays for Real-Time Monitoring of Air Traffic. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 121-122
[Identifiability: Dimensionality].

Previous research has revealed that three-dimensional (3-D) display formats do not always improve user performance. This report describes an experiment to determine the utility of using a 3-D format for monitoring air traffic of a Department of Defense (DoD) real-time display. An overwhelming quantity of data must be assimilated by personnel monitoring a typical mission. Data from these missions must be monitored and crucial life and death decisions made by personnel within a short period of time. The need for a precise human engineered computer interface resulted in the development and laboratory testing of a 3-D display concept for monitoring a typical DoD air surveillance display. In addition, the 3-D format was augmented using a two-dimensional (2-D) vertical bar graph directly beneath to provide users with additional information (i.e., signal strength) about displayed objects in the 3-D space. The 2-D, 3-D, and 3-D (augmented with vertical bar graph) displays were user tested for accuracy and performance. Results from this analysis revealed that user response times were decreased by 23% with a reduction in errors of 60% using the standard 3-D display. Additional testing is needed to determine the benefit of the vertical bar graph.

Tabachneck, H. J. M. and H. A. Simon (1994). What You See Is What You Get -- But Do You Get What You See? Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 293-294
[Visibility, Identifiability: Dimensionality].

Visualization can be very powerful. But can we over-visualize? This paper describes three experiments that show that visualization without proper grounding in the underlying knowledge base could be detrimental to understanding. Although we concentrate on graphs, the conclusions should hold for diagrams and icons as well. Visualization needs to be seen as but one aspect of what is needed to understand a concept. The visual aspect of a concept can be extremely helpful and enlightening -- but without thorough connections to its non-visual aspects, such as verbally expressed causal mechanisms, it can be but so many lines on paper.

Wickens, C. D., D. H. Merwin and E. L. Lin (1994). "Implications of graphics enhancements for the visualization of scientific data: Dimensional integrality, stereopsis, motion, and mesh." Human Factors **36**(1): 44-61
[Identifiability: Dimensionality, Structural Integrity: Depth Cues].

Examined the effectiveness of 4 techniques (dimensional integrality, stereo, data motion and rotation, and mesh) to assist scientists in evaluating multidimensional data. 14 graduate and undergraduate students viewed a series of complex 3D data sets, each representing an underlying complex surface, from which a set of discrete points or observations were sampled. From each sample they answered questions that required focus of attention on certain data points or integration across varying numbers of data points and dimensions. After a number of samples were viewed from each surface, Ss were tested for their retention of the surface characteristics. In Exp 1, 3D representations supported superior performance to 2D representations, but only for more integrative questions. In Exp 2, stereoptic views of a 3D display also supported performance, but the ability to rotate the data space and the presence of a mesh surface connecting the points did not. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

Wickens, C. D., S. Miller and M. Tham (1994). The Implications of Data-Link for Representing Pilot Request Information on 2D and 3D Air Traffic Control Displays. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 61-65
[Identifiability: Dimensionality].

Twenty-four subjects (seven ATC specialists and 17 pilots trained in fundamental ATC skills), performed a simulation in which they were required to evaluate pilot requests for flight plan changes, issued by aircraft depicted on their display. Some requests could be safely granted, whereas others would bring about a mid-air conflict with other aircraft. Subjects evaluated the requests in the context of an airspace depicted on either a conventional 2D planar display or a 3D perspective display. Requests were presented either as voice messages or were displayed visually, as if relayed via data-link, either printed at the bottom of the display or represented as vectors, emanating in the requested direction from the requesting aircraft. The results indicated that performance was generally equivalent with the 2D and the 3D display and was best with the auditory-verbal request mode. It was considerably slower with the print mode, presumably because of the greater scanning required. The spatial vector mode offered performance that was faster than print, but considerably less accurate. Particular deficiencies were noticed with the vector mode when it was used to present complex 3-dimensional requests in the context of the 3-dimensional display.

Wickens, C. D. and T. T. Prevett (1995). "Exploring the dimensions of egocentricity in aircraft navigation displays." Journal of Experimental PsychologyApplied **1**(2): 110-135
[Identifiability: Dimensionality].

Researchers explain a model of navigation that proposes that local guidance and global awareness are better supported by more, and less, egocentric displays, respectively. Greater egocentrism is created by perspective viewing, map rotation, and viewpoint positions that correspond to the axis of control. The model was tested in an experiment in which 40 pilots flew simulated landings with displays that varied the degree of egocentrism between a fully egocentric viewpoint, 3 distances of exocentric 3-dimensional viewpoints, and a 2-dimensional planar display. The results generally supported model predictions: The egocentric viewpoint supported best guidance, whereas the mid-distance exocentric viewpoint supported best global awareness. Implications of the model for the design of flight displays in particular, and navigational displays in general, are discussed. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

Wickens, C. D. and S. Todd (1990). Three Dimensional Display Technology for Aerospace and Visualization. Proceedings of the Human Factors Society 34th Annual Meeting 1479-1483 [Identifiability: Dimensionality].

The similarities and contrasts between scientific visualization, and the tasks imposed on the pilot and air traffic controller are highlighted. Relevant principles for 3 dimensional display design for both of these applications are stated, and an experiment is described which contrasts four graphical formats across a number of tasks involving the interpretation of a hypothetical set of scientific data. The tasks vary in the degree to which focused attention vs. integration is involved. The graphical formats were either 2 or 3D renderings and either did or did not contain contours to emphasize objectness. The results revealed that emergent features, created either by objectness or 3 dimensionality, facilitated integration performance. However, 3 dimensionality generally slowed performance on all tasks.

Williams, H. P. and C. D. Wickens (1991). Electronic Map Interpretation in a Dual-Task Context. Proceedings of the Human Factors Society 35th Annual Meeting 92-96
[Identifiability: Dimensionality, Sequential Clarity Navigation].

The present experiment was designed to assess the extent to which spatial and verbal-analytic (VA) information processing resources are used in performing a simulated aircraft navigation task. Subjects were required to decide whether a "match" or a "mismatch" existed between a schematic 3D perspective forward field of view and a 2D top-down map. On dual-task trials, this navigation task was concurrently performed with either a VA side-task or with one of two tracking tasks. The data suggest that a VA strategy was most likely to be used when stimuli were simple or were mismatches, whereas a spatial mental rotation strategy was apparently used to confirm complex match stimuli. These results indicate that it may be possible to specify conditions wherein navigation is likely to compete for resources critical to other cockpit activities, such as aircraft control and communication.

Zenyuh, J. P., J. M. Reising, S. Walchli and D. Biers (1988). A Comparison of a Stereographic 3-D Display versus a 2-D Display Using an Advanced Air-to-Air Format. Proceedings of the Human Factors Society 32nd Annual Meeting 53-57
[Identifiability: Dimensionality].

This study compared the relative abilities of a stereoscopic 3-D display versus a conventional 2-D display to provide spatial location information. The evaluation was conducted as a part mission, full-task simulation in the context of an air-to-air fighter mission. A dual task paradigm was employed requiring the subjects to acquire situation awareness of their immediate air-to-air environment while simultaneously performing a simple flight tasks. Situation awareness was defined as the ability to visually search a spatial quadrant of the air-to-air situation display relative to the ownship symbol and identify the number of aircraft symbols in a given target group found in that quadrant. The simulated flight task was a two-axis tracking task on a dynamic Head-Up Display format, using a force-stick controller. The subject's response speed and accuracy on the search task and deviations from the given track on the flight task were used as performance measures in this study. The results showed a significant accuracy performance advantage for those formats presented with the stereoscopic 3-D display.

Interaction Techniques

Bordegoni, M. (1994). “Parallel Use of Hand Gestures and Force-Input Device for Interacting with 3D and Virtual Reality Environments.” International Journal of Human-Computer Interaction **6**(4): 391-413
[Visibility, Identifiability: Interaction Techniques].

User interfaces of current 3D and virtual reality environments require highly interactive input/output (I/O) techniques and appropriate input devices, providing users with natural and intuitive ways of interacting. This paper presents an interaction model, some techniques, and some ways of using novel input devices for 3D user interfaces. The interaction model is based on a tool-object syntax, where the interaction structure syntactically simulates an action sequence typical of a human's everyday life: One picks up a tool and then uses it on an object. Instead of using a conventional mouse, actions are input through two novel input devices, a hand- and a force-input device. The devices can be used simultaneously or in sequence, and the information they convey can be processed in a combined or in an independent way by the system. The use of a hand-input device allows the recognition of static poses and dynamic gestures performed by a user's hand. Hand gestures are used for selecting, or acting as, tools and for manipulating graphical objects. A system for teaching and recognizing dynamic gestures, and for providing graphical feedback for them, is described.

Chuah, M. C., S. F. Roth, J. Mattis and J. Kolojejchick (1995). SDM: Selective Dynamic Manipulation of Visualizations. Proceedings of the ACM Symposium on User Interface Software and Technology 61-70
[Identifiability: Dimensionality, Identifiability: Interaction Techniques].

In this paper we present a new set of interactive techniques for 2D an 3D visualizations. This set of techniques is called SDM (Selective Dynamic Manipulation). Selective, indicating our goal for providing a high degree of user control in selecting an object set, in selecting interactive techniques and the properties they affect, and in the degree to which a user action affects the visualization. Dynamic, indicating that the interactions all occur in real-time and that interactive animation is used to provide better contextual information to users in response to an action or operation. Manipulation, indicating the types of interactions we provide, where users can directly move objects and transform their appearance to perform different tasks. While many other approaches only provide interactive techniques in isolation, SDM supports a suite of techniques which users can combine to solve a wide variety of problems.

Hancock, P. A. (1996). “Effects of control order, augmented feedback, input device and practice on tracking performance and perceived workload.” Ergonomics **39**(9): 1146-1162
[Identifiability: Interaction Techniques, Input Compatibility].

In service of virtual interface design processes, examined the effects of track order, knowledge, trackball or mouse control device, and the extent of practice on tracking performance and associated mental workload. Tracking was assessed by root mean square error. Subjective workload was measured using both the NASA Task Load Index and the Subjective Workload Assessment Technique. Results indicate that tracking error and subjective workload both increased non-proportionally with track order. Trackball use resulted in more accurate performance and was judged to be of lower subjective workload than mouse. Improved second-order tracking was retained even after a 30-day rest interval. Decrease in workload followed performance improvement in both initial acquisition and subsequent retention phases. (PsycLIT Database Copyright 1996 American Psychological Assn, all rights reserved)

Hix, D., J. N. Templeman and R. J. K. Jacob (1995). Pre-Screen Projection: From Concept to Testing of a New Interaction Technique. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 226-233
[Identifiability: Interaction Techniques, Familiarity].

Pre-screen projection is a new interaction technique that allows a user to pan and zoom integrally through a scene simply by moving his or her head relative to the screen. The underlying concept is based on real-world visual perception, namely, the fact that a person's view changes as the head moves. Pre-screen projection tracks a user's head in three dimensions and alters the display on the screen relative to head position, giving a natural perspective effect in response to a user's head movements. Specifically, projection of a virtual scene is calculated as if the scene were in front of the screen. As a result, the visible scene displayed on the physical screen expands (zooms) dramatically as a user moves nearer. This is analogous to the real world, where the nearer an object is, the more rapidly it visually expands as a person moves toward it. Further, with pre-screen projection a user can navigate (pan and zoom) around a scene integrally, as one unified activity, rather than performing panning and zooming as separate tasks. This paper describes the technique, the real-world metaphor on which it is conceptually based, issues involved in iterative development of the technique, and our approach to its empirical evaluation in a realistic application testbed.

Houde, S. (1992). Iterative Design of an Interface for Easy 3-D Direct Manipulation. Proceedings of ACM CHI'92 Conference on Human Factors in Computing Systems 135-142
[Identifiability: Interaction Techniques, Input Compatibility].

Although computer tools for 3-D design applications are now widely available for use on personal computers, they are unnecessarily difficult to use. Conventions for establishing and manipulating views of 3-D objects require engineering-oriented dialogues that are foreign to most users. This paper describes the iterative design and testing of a new mechanism for moving 3-D objects with a mouse-controlled cursor in a space planning application prototype. Emphasis was placed on developing a design which would make 3-D interaction more intuitive by preserving users' experiences with moving objects in the real, physical world. Results of an informal user test of the current interface prototype are presented and implications for the development of a more general direct manipulation mechanism are discussed.

Hudson, S. E. (1992). “Adding Shadows to a 3D Cursor.” ACM Transactions on Graphics **11**(2): 193-199
[Identifiability: Interaction Techniques].

In this note, a technique for creating shadows for a 3D cursor in a depth-buffer has been presented. This technique is simple to implement and can make use of existing depth-buffer hardware and software. Because it is efficient enough to respond interactively and can cast shadows over arbitrary backdrops, this technique can be employed in a range of 3d-positioning techniques to improve the perception of depth and spatial relationships within a scene.

Kabbash, P. and W. Buxton (1995). The "Prince" Technique: Fitts' Law and Selection Using Area Cursors. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 273-279
[Identifiability: Interaction Techniques].

In most GUIs, selection is effected by placing the point of the mouse-driven cursor over the area of the object to be selected. Fitts' law is commonly used to model such target acquisition, with the term A representing the amplitude, or distance, of the target from the cursor, and W the width of the target area. As the W term gets smaller, the index of difficulty of the task increases. The extreme case of this is when the target is a point. In this paper, we show that selection in such cases can be facilitated if the cursor is an area, rather than a point. Furthermore, we show that when the target is a point and the width of the cursor is W, that Fitts' law still holds. An experiment is presented and the implications of the technique are discussed for both 2D and 3D interfaces.

Liggett, K. K., J. M. Reising, D. J. Beam and D. C. Hartsock (1993). The Use of Aiding Techniques and Continuous Cursor Controllers to Designate Targets in 3-D Space. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting 11-15
[Identifiability: Interaction Techniques, Input Compatibility].

The purpose of this study was to determine the effects of three variables on target designation tasks using three-dimensional (3-D) maps. Variable 1: two continuous control techniques, Variable 2: two aiding techniques, and Variable 3: two target densities. The two continuous controllers used were an ultrasonic hand tracker and a joystick. The two aiding techniques were referred to as simple and enhanced aiding. Simple aiding consisted of a color change to the target when the cursor penetrated the target volume. Enhanced aiding consisted of an algorithm (Osga, 1991) that "pulled" the cursor to the closest target and then changed its color. The two target densities were high (16 targets) and low (8 targets). Results showed that the hand tracker provided the best performance with respect to total target designation time. Enhanced aiding provided the best performance in terms of both total target designation time and percent errors. For the density variable, the common speed-accuracy trade-off was present -- the low density condition had faster total target designation times, but the high density had less percent errors.

Solz, T. J., J. M. Reising, K. K. Liggett, T. Lohmeyer and D. C. Hartsock (1994). The Use of Aiding Techniques and Varying Depth Volumes to Designate Targets in 3-D Space. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 1-5
[Identifiability: Interaction Techniques, Input Compatibility].

The purpose of this study was to determine the effectiveness of a hand tracker to designate targets using a three-dimensional (3-D) map. Three variables were manipulated: 1) hand tracker active volume, 2) aiding technique, and 3) target density. There were three different volumes (large, medium and small) in which the hand tracker operated. Each volume represented cockpit space in which hand tracker movements correlated to cursor movements on the screen. Two aiding techniques were referred to as contact aiding and proximity aiding. Contact aiding consisted of a color shade change to the target when the cursor penetrated the target volume. Proximity aiding consisted of an algorithm that selected the target closest to the cursor and thus changed its color shade. Two target densities, high (16 targets) and low (8 targets), were used.

Speed and accuracy were measured in the designation of targets using a hand tracker. Results showed that proximity aiding in the medium volume space yielded the best performance.

Ware, C. and L. Slipp (1991). Using Velocity Control to Navigate 3D Graphical Environments: A Comparison of Three Interfaces. Proceedings of the Human Factors Society 35th Annual Meeting 300-304
[Identifiability: Interaction Techniques, Sequential Clarity].

Three velocity control interfaces to three dimensional virtual environments are compared. The interface devices are: a six degree of freedom position sensor, a six degree of freedom isometric joystick, and a conventional mouse in conjunction with a soft control panel displayed on the monitor. In each interface the devices are used to control velocity, and all make use of a quadratic function to map the input to the viewpoint velocity. We use two structured exploration tasks to assess the usability of the different interfaces. In the first task an interviewing technique is used in conjunction with an exploration task which involved examining widely spaced details of the 3D scene. The second task is designed to reveal how well users can interact at different scales using the different devices. Subjects are required to navigate through a tube which varies over four orders of magnitude in size. The results show that subject's behavior is highly constrained by the local size of the tube: they maintained a constant velocity relative to the local size of the tube. They also showed differences in the effectiveness of the different devices in determining traversal rate that the positioning device and the control panel were about equally effective for fast navigation, and both are better than the isometric joystick.

Wu, J.-R. and M. Ouhyoung (1995). A 3D Tracking Experiment on Latency and its Compensation Methods in Virtual Environments. Proceedings of the ACM Symposium on User Interface Software and Technology 41-49
[Identifiability: Interaction Techniques].

In this paper, we conducted an experiment on the latency and its compensation methods in a virtual reality application using an HMD and a 3D head tracker. Our purpose is to make a comparison both in the simulation and in the real task among four tracker prediction methods: the Grey system theory based prediction proposed in 1994, the Kalman filtering which is well-known and wide-spreading since 1991, a simple linear extrapolation, and the basic method without prediction. In our 3D target tracing task that involved eight subjects, who used their head motion to trace a flying target in random motion, we have found that when the system latency is 120ms, two prediction methods, Kalman filtering (not inertial-based) and Grey system prediction, are significantly better than the one without prediction, and the former two methods are equally well in performance. Typical motion trajectories of four methods in simulation are plotted, and jittering effects are examined. In terms or jittering at 120ms prediction length, Kalman filtering was evaluated to have the largest.

Zhai, S. (1993). Investigation of Feel for 6DOF Inputs: Isometric and Elastic Rate Control for Manipulation in 3D Environments. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting 323-327
[Identifiability: Interaction Techniques].

An increasing need exists for both a theoretical basis and practical human factors guidelines for designing and selecting high degree-of-freedom (DOF) computer input devices for

3D interactive environments such as telerobotic and virtual reality systems. This study evaluates elastic versus isometric rate control devices, in a 3D object positioning task. An experiment was conducted with a stereoscopic virtual reality system. The results showed that the elastic rate controller facilitated faster task completion time in the first of four phases of the experiment. The results are discussed in light of psychomotor literature. While the richer proprioceptive feedback afforded by an elastic controller is necessary for achieving superior performance in the early stages of learning, subjects performed equally well with the isometric controller in later learning stages. The study provides evidence to support a theory of skill shift from closed-loop to open-loop behaviour as learning progresses.

Zhai, S., W. Buxton and P. Milgram (1994). The "Silk Cursor": Investigating Transparency for 3D Target Acquisition. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 459-464
[Identifiability: Interaction Techniques].

This study investigates dynamic 3D target acquisition. The focus is on the relative effect of specific perceptual cues. A novel technique is introduced and we report on an experiment that evaluates its effectiveness. There are two aspects to the new technique. First, in contrast to normal practice, the tracking symbol is a volume rather than a point. Second, the surface of this volume is semi-transparent, thereby affording occlusion cues during target acquisition. The experiment shows that the volume/occlusion cues were effective in both monocular and stereoscopic conditions. For some tasks where stereoscopic presentation is unavailable or infeasible, the new technique offers an effective alternative.

Perceptual Grouping

Bennett, K. B., M. L. Toms and D. D. Woods (1993). "Emergent features and graphical elements: Designing more effective configural displays." Human Factors **35**(1): 71-97 [Identifiability: Perceptual Grouping].

Conducted 2 empirical studies with 20 students (aged 19-35 yrs) to investigate the effectiveness of configural displays in allowing the extraction of both high-level constraints and low-level data (LLD), using a laboratory analog of a complex, dynamic task modeled on a real-world domain. Performance with a configural display, which highlighted the LLD, was compared with performance with a bar graph display. For the extraction of information about high-level constraints in a memory probe task, the configural display significantly increased accuracy with no cost in latency. For LLD there were no differences in accuracy across the 2 display conditions, but there was a significant cost in latency with the configural display. However, this cost was dependent on both experience and system state. Results suggest that configural displays can be designed to support the extraction of both high-level constraints and LLD in complex, dynamic domains. (PsycLIT Database Copyright 1993 American Psychological Assn, all rights reserved)

Carswell, C. M. and C. D. Wickens (1987). "Information integration and the object display: An interaction of task demands and display superiority." Ergonomics **30**(3): 511-527 [Identifiability: Perceptual Grouping].

Compared 2 graphical display formats, using 2 tasks, varying in their demands to integrate multiple information sources. An object display utilized different dimensions of a single perceptual object to display task-relevant information. A contrasting bar graph technique used the same dimension of separate objects to present identical information. In Exp I, 24 Ss (aged 18-30 yrs) used both displays to perform a simulated process control task in which integration of information from several time-varying sources was required. In Exp II, 20 additional Ss (aged 18-26 yrs) used both displays in a nonintegration task that required monitoring for particular values of 6 independent system outputs. Results of the integration experiment reveal that performance was superior when the object display was used. In the nonintegration task, the bar graphs provided more efficient performance. (French, German & Japanese abstracts) (PsycLIT Database Copyright 1987 American Psychological Assn, all rights reserved)

Carswell, C. M. and C. D. Wickens (1990). "The perceptual interaction of graphical attributes: Configurality, stimulus homogeneity, and object integration." Perception and Psychophysics **47**(2): 157-168
[Identifiability: Perceptual Grouping].

13 groups, each with 9 men and women, performed a battery of speeded classification tasks in which 13 stimulus sets, each composed of attributes commonly used in the design of graphs, were submitted to the performance-based diagnostics of integrality and configurality. Analyses suggest a continuum of configurality among the stimulus sets, with little evidence for integral graphical attributes. The configural pattern of results was more common when 2 identical dimensions were paired (homogeneous stimuli) than when 2 different dimensions were paired (heterogeneous stimuli). However, there was no evidence that pairs of dimensions belonging to a single object (object integration) were any more configural than dimensions belonging to different

objects. Object integration was, however, consistently related to inefficient performance in tasks requiring the filtering of 1 of 2 component dimensions. (PsycLIT Database Copyright 1990 American Psychological Assn, all rights reserved)

Carswell, C. M. and C. D. Wickens (1996). "Mixing and matching lower-level codes for object displays: Evidence for two sources of proximity compatibility." Human Factors **38**(1): 1-22 [Identifiability: Dimensionality, Identifiability: Perceptual Grouping].

Evaluated the utility of object displays for integration tasks, focusing specifically on whether object display advantages are a function of the lower-level codes used to represent raw data values. In each of 2 experiments, 15 adult Ss' performance with object and separable configurations of mixed or matching pairs of lower-level codes was compared for system state classification tasks requiring either (1) comparisons of values or (2) identification of conjunctions of values. Object displays formed with matched codes were more likely to facilitate comparisons, whereas object displays formed from mixed codes were more likely to facilitate conjunction identification. These data suggest that object display advantages for integration may be due to relational properties, emergent features, or the efficient processing of the lower level codes themselves. (PsycLIT Database Copyright 1996 American Psychological Assn, all rights reserved)

Chignell, M. H., F. Poblete and S. Zuberec (1993). An Exploration in the Design Space of Three-Dimensional Hierarchies. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting 333-337
[Visibility, Identifiability: Perceptual Grouping, Structural Integrity].

Three dimensional hierarchies may be used to visualize and manipulate a variety of types of information, including tables of contents, taxonomies, fault trees, and code libraries in languages such as C++. Based on a review of the literature, it is suggested that visual scanning and perceived organization are two main processes involved in the understanding and use of 3D hierarchies. A general system (Info-TV) is described which can be used to explore a 3D design space. Info-TV is an information tree visualization system that takes hierarchical information and displays it in a three dimensional format. It has been designed to include the major parameters of the tree visualization design space and can be used to explore this space. Two experiments are reported that assess the effect of different tree shapes on different tasks. The results of these experiments are then discussed in terms of their implications for the design space of three-dimensional hierarchies.

Davi, M. and D. R. Proffitt (1993). "Frames of reference and distinctive figural characteristics affect shape perception." Journal of Experimental Psychology Human Perception and Performance **19**(4): 867-877
[Cognition and Perception, Identifiability: Perceptual Grouping].

In 4 experiments it was found that global frameworks and local distinctive figural characteristics influenced the perception of shape and of pointing. In Exps 1 and 2, Ss were asked to mark the center of the middle figure in array of 3 aligned figures (either triangles or squares). Displacements of the center indicated a perceived deformation of the shapes. In Exp 3, Ss were asked to adjust the height of triangles in arrays similar to those in Exp 1. Height adjustments made along the axis of apparent pointing resulted in extents that were shorter than the height necessary to form equilateral triangles. In Exp 4, stimuli were isosceles triangles in which the apparent distortion had been nulled; however, Ss continued to perceive them as pointing in a direction consistent with their alignment, and hence shape distortion cannot be the cause of pointing. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

Hansen, J. P. (1995). "An experimental investigation of configural, digital, and temporal information on process displays." Human Factors **37**(3): 539-552
[Identifiability: Perceptual Grouping].

Investigated the detection of a temporal event by comparing perceptual performance in terms of reaction time (RT), hit rate, and number of false alarms on 4 separated and integrated display formats with and without historical information with 11 graduate students. Exp 1 showed that instantaneous displays were perceived faster than historical displays on high-rate events but not on low-rate events. The hit rate and the number of false alarms was higher on integrated displays than on separated displays. Exp 2 used data with random noise added. Graphical integration across time and across the 8 variables were important for the ability to see trends in the presence of noise. Adding digital information to graphical displays was found to decrease RT in general, but the hit rate may be reduced by adding numbers on integrated displays without a temporal dimension. (PsycLIT Database Copyright 1997 American Psychological Assn, all rights reserved)

Koike, H. (1993). "The Role of Another Spatial Dimension in Software Visualization." ACM Transactions on Information Systems **11**(3): 266-286
[Identifiability: Dimensionality,Identifiability: Perceptual Grouping, Familiarity].

The primary objective of this article is to demonstrate the use of 3D-computer graphics in visualizing shapeless software information by focusing on performance monitoring of parallel/concurrent computer systems. Issues are addressed from two different perspectives: expressiveness of output media and user cognition. The former describes the limitations of 2D output media. The latter refers to a user's cognitive load when using 2D representations in a multiple-window environment. We show how these problems can be minimized by using a 3D framework. A prototype visualization system called VOGUE has been developed. A 3D framework is used to visualize the execution pattern of two parallel/concurrent computer systems: an electric power control system and a parallel manipulator system. Through these visualizations, we show the effectiveness of our framework. The applications of 3D frameworks to other kinds of software information are also described.

Liu, Y. (1989). Use of Computer Graphics and Cluster Analysis in Aiding Relational Judgment. Proceedings of the Human Factors Society 33rd Annual Meeting 345-349
[Identifiability: Perceptual Grouping, Structural Integrity, Familiarity].

An experiment is conducted to investigate the use of computer graphics and cluster analysis in aiding human relational judgment. The experimental stimuli were similarity matrices from real-world data sources. The experimental tasks required the subjects to detect the number of clusters or to judge the similarity value between a designated pair of objects in the displayed matrix. Each matrix was either ordered randomly or arranged according to the results of cluster analysis. Each matrix was displayed in one of four schemes: number scheme, color scheme, size scheme or 3-D vertical line scheme. The results indicated that the cluster-ordered displays greatly facilitated cluster detection performance in three out of the four display schemes, with the 3-D line scheme as the only exception. Matrix ordering had no effect on the value judgment task. The proximity compatibility principle (Wickens, 1987) and theories of perceptual grouping (Garner, 1976; Pomerantz, 1981) provided predictions and were tested in this experiment. Theoretical and practical implications were also discussed.

Mukherjea, S., J. D. Foley and S. E. Hudson (1994). Interactive Clustering for Navigating in Hypermedia Systems. Proceedings of the ECHT'94 European Conference on Hypermedia Technologies 136-145
[Visibility, Identifiability: Perceptual Grouping, Sequential Clarity: Navigation, Familiarity].

This paper talks about clustering related nodes of an overview diagram to reduce its complexity and size. This is because although overview diagrams are useful for helping the user to navigate in a hypermedia system, for any real-world system these become too complicated and large to be really useful. Both structure-based and content-based clustering are used. Since the nodes can be related to each other in different ways, depending on the situation different clustered views will be useful. Hence, it should be possible to interactively specify the clustering conditions and examine the resulting views. We present efficient clustering algorithms which can cluster the information space in real-time. We talk about the Navigational View Builder, a tool that allows the interactive development of overview diagrams. Finally, we propose a 3-dimensional approach for visualizing these abstracted views.

Nygren, E., M. Lind, M. Johnson and B. Sandblad (1992). The Art of the Obvious. Proceedings of ACM CHI'92 Conference on Human Factors in Computing Systems 235-239
[Identifiability: Perceptual Grouping].

In addition to normal reading, knowledge can be gained from a paper document by pattern recognition and encoding of characteristics of the information media. There are reasons to believe that this can be done automatically with very little attentional demand. The knowledge gained is accessible to consciousness and can be used for task components like orientation, navigation, detection of changes and as a complement to normal reading. When information is computerized, and is read from a screen instead of from a paper, the conditions for automaticity are often radically changed. In most cases the reader has to gain the corresponding knowledge by effortful cognitive processes. This means adding to the cognitive load leaving less attentional capacity for the main task at hand. This problem can be avoided by a careful analysis of a reading task into its automatic and non-automatic components, followed by a dedicated user interface design where information relevant for orientation, navigation etc is presented in a way that the reader can perceive rather than read.

Pomerantz, J. R. (1981). Perceptual Organization in Information Processing. Perceptual Organization. M. Kubovy and J. R. Pomerantz. Hillsdale, NJ, Erlbaum: 141-180
[Identifiability: Perceptual Grouping].

Analysis of perceptual organization can be viewed as a description based on the stimulus. This articles fits such stimulus characteristics into an information processing perspective.
Robertson, G. G., J. D. Mackinlay and S. K. Card (1991). Cone Trees: Animated 3D Visualizations of Hierarchical Information. Proceedings of ACM CHI'91 Conference on Human Factors in Computing Systems 189-194

[Visibility, Identifiability: Dimensionality, Identifiability: Perceptual Grouping].

The task of managing and accessing large information spaces is a problem in large scale cognition. Emerging technologies for 3D visualization and interactive animation offer potential solutions to this problem, especially when the structure of the information can be visualized. One of these Information Visualization techniques, called the Cone Tree, is used for visualizing hierarchical information structures. The hierarchy is presented in 3D to maximize effective use of available screen space and enable visualization of the whole structure. Interactive animation is used to shift some of the user's cognitive load to the human perceptual system.

A.3. Structural and Aesthetic Integrity: Present information in a stable, coherent, comprehensible layout.

Fishkin, K. and M. C. Stone (1995). Enhanced Dynamic Queries via Movable Filters. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 415-420
[Structural Integrity, Input Compatibility, Familiarity].

Traditional database query systems allow users to construct complicated database queries from specialized database language primitives. While powerful and expressive, such systems are not easy to use, especially for browsing or exploring the data. Information visualization systems address this problem by providing graphical presentations of the data and direct manipulation tools for exploring the data. Recent work has reported the value of dynamic queries coupled with two-dimensional data representations for progressive refinement of user queries. However, the queries generated by these systems are limited to conjunctions of global ranges of parameter values. In this paper, we extend dynamic queries by encoding each operand of the query as a Magic Lens filter. Compound queries can be constructed by overlapping the lenses. Each lens includes a slider and a set of buttons to control the value of the filter function and to define the composition operation generated by overlapping the lenses. We demonstrate a system that supports multiple, simultaneous, general, real-valued queries on databases with incomplete data, while maintaining the simple visual interface of dynamic query systems.

Flowers, J. H. and T. A. Hauer (1993). “"Sound" alternatives to visual graphics for exploratory data analysis. 22nd Annual Meeting of the Society for Computers in Psychology: Symposium on data visualization (1992, St Louis, Missouri).” Behavior Research Methods, Instruments and Computers **25**(2): 242-249
[Structural Integrity].

Examined whether efficient exploratory data analysis (EDA) may be aided by succinct, but informative, graphical representations (e.g., Tukey plots) that convey information about central tendency, variability, and shape of distributions, and that permit detection of outliers. Using research strategies adapted from studies of cross-modal perceptual equivalence in 3 experiments with a total of 50 university students, it is shown how auditory analogies of such displays may offer an effective alternative to visual plots for EDA.

Hohl, H., J. Herczeg and M. Ressel (1993). An Interactive Design Environment for Graphical Browsers. Proceedings of the Fifth International Conference on Human-Computer Interaction 585-590
[Structural Integrity, Sequential Clarity: Navigation].

Browsing, viewed as an integral approach to exploring and directly manipulating large and complex information spaces, crucially depends on adequate graphical presentation and interaction techniques to support navigation. Going beyond available user interface development environments, which are poor in representing and graphically presenting application-specific information structures, we describe an integrated approach to developing domain-specific browsing tools. A set of extensible and reusable construction kits for browsing form an application-independent framework that provides powerful mechanisms for representing, presenting, and accessing complex information structures. This framework is integrated within a browser design environment which offers higher-level tools for building or modifying domain-specific browsers interactively. These tools are designed to be used by both application developers and end users, i.e. domain experts, to adapt and tailor browsers according to a particular application domain or to specific user needs.

Hovestadt, V., O. Gramberg and O. Deussen (1995). Hyperbolic User Interfaces for Computer Aided Architectural Design. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 304-305
[Structural Integrity, Identifiability, Familiarity].

We present basic ideas and a prototypical implementation of a graphical user interface intended for the architectural design process. The interface integrates CAD-like object manipulation and navigation through large data sets. Navigation and working area are not separated as done in prior work. Geometric transformations produce a deformed but controllable display of the data in the border area of the working window while normal working is possible in the untransformed center. The arrangement allows the user to shift directly from construction tasks to navigation tasks. Data reduction techniques have been implemented in order to reduce the cost of transformation and display.

Mukherjea, S., J. D. Foley and S. Hudson (1995). Visualizing Complex Hypermedia Networks through Multiple Hierarchical Views. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 331-337
[Structural Integrity, Example].

Our work concerns visualizing the information space of hypermedia systems using multiple hierarchical views. Although overview diagrams are useful for helping the user to navigate in a hypermedia system, for any real-world system they become too complicated and large to be really useful. This is because these diagrams represent complex network structures which are very difficult to visualize and comprehend. On the other hand, effective visualizations of hierarchies have been developed. Our strategy is to provide the user with different hierarchies, each giving a different perspective to the underlying information space to help the user better comprehend the information. We propose an algorithm based on content and structural analysis to form hierarchies from hypermedia networks. The algorithm is automatic but can be guided by the user. The multiple hierarchies can be visualized in various ways. We give examples of the implementation of the algorithm on two hypermedia systems.

Waterworth, J. A. and M. H. Chignell (1991). "A Model of Information Exploration." Hypermedia **3**(1): 35-58
[Structural Integrity, Familiarity].

A three-dimensional model of information exploration is presented. By pointing to three distinct dimensions of exploration, we attempt to clarify the respective roles of the human and the system in browsing and information retrieval, and to characterise alternative interaction styles to maximise retrieval effectiveness. We illustrate the applicability of our model of exploration by describing eight paradigmatic cases of information exploration that represent different vertices of the model. We also briefly describe an initial experiment that attempted to assess the pragmatic impact of various combinations of exploration features. We then discuss methods for integrating hypermedia and information retrieval into general information exploration systems and discuss some of the processes that people use in information exploration. We conclude with a plea for the development of hybrid information systems combining exploration features in the most appropriate way according to the task needs of users.

Wickens, C. D., C. C. Liang, T. Prevett and O. Olmos (1996). "Electronic maps for terminal area navigation: Effects of frame of reference and dimensionality." International Journal of Aviation Psychology **6**(3): 241-271
[Structural Integrity, Familiarity].

Examined how 2 aspects of electronic flight desk displays, map rotation and dimensionality influence pilot performance. In Exp 1, 32 student pilots simulated a landing approach. The Ss' ability to maintain flight path and demonstrate awareness of surrounding terrain were assessed, as a rotating vs fixed-map display was crossed with a 2-dimensional (2D) vs 3-dimensional (3D) perspective map. Rotating displays supported better flight path guidance and did not harm terrain awareness task performance. The 3D displays led to substantial cost for vertical control, but did not differ from 2D displays in lateral control. In Exp 2, 8 student pilots flew with the rotating 2D display and an improved rotating 3D display, designed to reduce the ambiguity of altitude information. Vertical control improved with the 3D display design improvement. Presentation of information in 3D for flight path control and terrain awareness is discussed.

Depth Cues

Adelson, S. J., J. Allen, A. N. Badre, L. F. Hodges and et al. (1993). "Performance comparison of multiple image depth and shape cues." International Journal of Human Computer Interaction 5(4): 347-360
[Identifiability: Depth Cues, Familiarity].

The effectiveness of 5 techniques (binocular parallax (BP), alternating horizontal parallax (AHP), alternating vertical parallax (AVP), motion parallax (MP), and MP in conjunction with the Pulfrich effect (PE)) were compared for shape and depth discrimination, using 18 male graduate students. This has implications for human-computer interaction in which the user must interact with display information that is organized on multiple axes. BP, closely followed by MP and PE, was most effective for the depth discrimination task in terms of both correctness and response time. AHP and AVP provided cues for distinguishing between foreground and background in a scene but did not provide cues that were intuitively translated into depth. Response time of Ss for the shape discrimination task was fastest with AVP and AHP. For depth discrimination, Ss preferred BP. For shape discrimination, BP and MP were both highly rated.

Bennett, C. T., W. W. Johnson, M. L. Braunstein, J. M. Flach and L. Wolpert (1988). Perspective Displays: The Control of Motion in 3-D Virtual Space. Proceedings of the Human Factors Society 32nd Annual Meeting 1359-1360
[Identifiability, Structural Integrity: Depth Cues, Familiarity].

Perspective displays have been used to better understand how people perceive self translation and rotation. Much of the early work in this are was conducted with cinematic displays and a passive observer. More recently, making use of lower cost, high speed graphics oriented computers, investigators have studied the interactive regulation of perspective scenes. The study of the active control of optical flow has both challenged some early hypotheses, and provided some insight into the impact that methodology has on the perception of perspective displays. The use of perspective displays has also expanded with the opportunity for people to work in 3-D virtual environments. Examples of such environments include work stations in the space shuttle, or indeed any hostile environment where the operator is remote from the viewing plane of a sensor. Such teleoperation has placed a burden on designers of such work stations to understand both the mathematical principles that underlay perspective, as well as the perceptual sensitivity to optical variables. The panel members will discuss the recent developments in the study of optical flow as it relates to the perception of computer generated virtual worlds, and the analytical and methodological techniques involved in the study of perspective displays. But, emphasis will be placed on optical flow and the perception/control of motion while observing perspective displays. The empirical and computational study of optical flow has led to a more complete understanding of the visual information used to control self motion. The term optical flow refers to the relative motion of surface texture elements during angular and/or translational transformation of an observer. Although the mathematical transformation of an entire image is computationally intense, the actual calculation of the movement of texture elements is not difficult. It is based on only three variables: slant angle, slant range, and velocity. Slant angle incorporates both azimuth and elevation of a surface point from the observer. Slant range is the actual line of sight distance between the observer and the texture element. Velocity, of course, incorporates both the speed and the direction of translation or rotation of the observer. It is important to remember that the term optical flow makes reference to the geometric relationship of surface points to an observer, and how that relationship changes as the observer moves. In using the term optical flow, it is not assumed that the observer can or does make appropriate use of the optical information. Optical flow merely makes reference to the physical stimuli. The term visual flow refers to those elements in the optical flow that are supra-threshold. Perspective displays are typically based on the graphical representation of a surface. At a minimum, these displays incorporate the density and compression gradients that describe the plane. Density is defined as the frequency of surface elements within a given viewing angle. Compression refers to the apparent decrease in distance between surface elements as distance from the observer increases. If we are to describe and quantify how a human operator uses a perspective display, we must be careful how we operationally define the very basic concepts discussed above. How such concepts have been quantified will serve as the central theme of the discussions.

Brown, M. E. and J. J. Gallimore (1995). "Visualization of Three-Dimensional Structure During Computer-Aided Design." International Journal of Human-Computer Interaction 7(1): 37-56 [Identifiability: Dimensionality, Structural Integrity: Depth Cues, Familiarity].

The visual image presented to an engineer using a computer-aided design (CAD) system influences design activities such as decision making, problem solving, cognizance of complex relationships, and error correction. Because of the three-dimensional (3-D) nature of the object being created, an important attribute of the CAD visual interface concerns the various methods of presenting depth on the display's two-dimensional (2-D) surface. The objective of this research is to examine the effects of stereopsis on subjects' ability to (a) accurately transfer to, and retrieve from, long-term memory spatial information about 3-D objects; and (b) visualize spatial characteristics in a quick and direct manner. Subjects were instructed to memorize the shape of a 3-D object presented on a stereoscopic CRT during a study period. Following the study period, a series of static trial stimuli were shown. Each trial stimulus was rotated (relative to the original) about the vertical axis in one of six 36{deg} increments between 0{deg} and 180{deg}. In each trial, the subject's task was to determine, as quickly and as accurately as possible, whether the trial object was the same shape as the memorized object or its mirrored image. One of the two cases was always true. To assess the relative merits associated with disparity and interposition, the two depth cues were manipulated in a within-subject manner during the study period and during the trials that followed. Subject response time and error rate were evaluated. Improved performance due to hidden surface is the most convincing experimental finding. Interposition is a powerful cue to object structure and should not be limited to late stages of design. The study also found a significant, albeit limited, effect of stereopsis. Under specific study object conditions, adding disparity to monocular trial objects significantly decreased response time. Response latency was also decreased by adding disparity information to stimuli in the study session.

Caird, J. K. and P. A. Hancock (1991). Perceived Spatial Layout of a Simulated Scene as a Function of Experience. Proceedings of the Human Factors Society 35th Annual Meeting 1447-1451
[Structural Integrity: Depth Cues, Expertise].

A critical question in simulation is the degree of correspondence or alignment between what is seen in a generated graphics world and it's intended actual physical structure. An allied concern, is the role of perceptual experience as a potential influence on this perceived spatial layout. The present experiment examined the potential for these perceived distortions. Eight observers estimated the location of nine object locations embedded in a graphical scene of a traffic intersection. Participants were asked to judge the relative and absolute distances between objects in the display. Half the subjects viewed the intersection after driving for thirty minutes through the simulated traffic world while the remaining participants did not receive any prior experience. A multidimensional scaling analysis revealed differences between simulator and no simulator experience groups for absolute and relative 3-D solutions. Scaled representations of actual and perceived spaces are discussed in the framework of a model of perceived spatial layout and with respect to human factors issues in the use of both simulated and virtual worlds.

Fitzmaurice, G. W., S. Zhai and M. H. Chignell (1993). "Virtual Reality for Palmtop Computers." ACM Transactions on Information Systems **11**(3): 197-218
[Structural Integrity: Depth Cues].

We are exploring how virtual reality theories can be applied toward palmtop computers. In our prototype, called the Chameleon, a small 4-inch hand-held monitor acts as a palmtop computer with the capabilities of a Silicon Graphics workstation. A 6D input device and a response button are attached to the small monitor to detect user gestures and input selections for issuing commands. An experiment was conducted to evaluate our design and to see how well depth could be perceived in the small screen compared to a large 21-inch screen, and the extent to which movement of the small display (in a palmtop virtual reality condition) could improve depth perception. Results show that with very little training, perception of depth in the palmtop virtual reality condition is about as good as corresponding depth perception in a large (but static) display. Variations to the initial design are also discussed, along with issues to be explored in future research. Our research suggests that palmtop virtual reality may support effective navigation and search and retrieval, in rich and portable information spaces.

Fowler, R. H., W. A. L. Fowler, A. Kumar and J. L. Williams (1995). Head-Coupled Stereo Display for Visualization in a Document Retrieval System using Associative Networks. Proceedings of the Eighteenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 360
[Structural Integrity: Depth Cues, Preference].

The system to be demonstrated provides head-coupled stereoscopic viewing of 3-d visual representations for document collections, associative term thesauri, and individual documents. This style of interface has been called "fish tank VR" and shown to be relatively effective for 3-d viewing and interaction tasks. The system also provides mechanisms to integrate query formulation across the visual representations. Supplying interaction techniques to access the system's several visual representations is one of the system's goals. The demonstration allows users to experiment with 3-d interaction in the highly interactive, iterative process of information retrieval.

Gallimore, J. J. and M. E. Brown (1993). "Visualization of 3-D Computer-Aided Design Objects." International Journal of Human-Computer Interaction **5**(4): 361-382
[Structural Integrity: Depth Cues, Input Compatibility, Evaluation].

There are many significant human factors issues associated with the design and visualization of complex, computer-generated images. One such issue is to determine the most effective techniques for providing engineers with realistic three-dimensional (3-D) objects. Differences in subjects' ability to discriminate between the shape of two 3-D, perspective, computer-aided design-type (CAD-type) objects were investigated for various levels of monocular coding techniques and the binocular cue stereopsis. Performance was assessed at all combinations of five levels of monocular cues and two levels of disparity. The task was similar to the classic mental rotation paradigm except that subjects were provided with the ability to rotate one of the objects using a two-dimensional (2-D) joystick. Results indicate that interposition was the only depth cue that significantly enhanced subject performance. One explanation for the lack of significance of stereopsis is that, for this particular task, depth information provided by disparity was not needed. Detailed analysis of object rotation data using an orientation index (OI) suggests that subjects employed a feature-by-feature comparison task strategy. With tools that can evaluate cognitive activity such as the mental rotation paradigm and orientation index, researchers can learn more about how designers visualize and understand 3-D CAD objects.

Leiser, D., Y. Bereby and A. Melkman (1995). "A Comparison of Display Methods for Spatial Point Layout." Behaviour and Information Technology **14**(3): 135-142
[Identifiability: Dimensionality, Structural Integrity: Depth Cues].

A series of six experiments compared several approaches to displaying 3D point information on a CRT screen. The methods used included perspective, motion, stereo, and numeric information, in various combinations. Measures included error rate and reaction times on three tasks, which all involved deciding whether a given configuration of dots exhibits a given property (collinearity, coplanarity, acute angle). Stereo proved to be the best method, being both faster and more accurate than the others. Simply presenting two perspective views is also effective, yet adding azimuthal motion under the subject's control is better on the most demanding task (coplanarity detection), while digital height information combined with a traditional top view (PPI) is slow, and especially inaccurate for coplanarity detection. Finally, the worst methods are the rotational interactive displays. Accuracy does not improve, whereas reaction times are considerably slower.

McClain, J. E. (1989). Hue and Disparity Interactions in Advanced Stereoscopic Aircraft Displays. Proceedings of the Human Factors Society 33rd Annual Meeting 1422-1426
[Structural Integrity: Depth Cues, Familiarity].

With the increased complexity of aircraft systems and their environment, 3-D stereoscopic system/control displays will offer great advantage over conventional two-dimensional (2-D) displays by presenting information more consistent with the pilot's 3-D perceptual experience and stereotypes. For such displays the interaction of Chromostereopsis (perceived depth created by hues) and stereopsis (depth effect created by disparity between the left and right visual fields of the observer) is important. The purpose of this research is to evaluate the interaction of chromostereopsis and artificially stimulated stereopsis on a stereoscopic CRT by determining the level of accuracy with which subjects can properly interpret the relative depth differences of adjacent symbols containing one of a combination of six levels of hue and seven stereoscopic disparities. This research demonstrated that hue, disparity, and the interaction of hue and disparity significantly influenced one's perception of depth on a stereoscopic monitor and that caution should be exercised by the stereoscopic 3-D display format designer when choosing hues to represent images located in close proximity on a stereoscopic display.

Merwin, D. H., M. A. Vincow and C. D. Wickens (1994). Visual Analysis of Scientific Data: Comparison of 3D Topographic, Color, and Gray Scale Displays in a Feature Detection Task. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 240-244 [Identifiability: Dimensionality, Structural Integrity: Depth Cues].

Several display techniques were compared for representing scientific data in the context of a feature detection task. The data sets were rendered on a Silicon Graphics workstation using four display formats: linearized gray scale; rainbow scale; reduced hue (blue-green-yellow-white) scale; and a 3D-topographic formal viewed in stereo. The task involved searching for features that were embedded in scientific data sets consisting of two spatial and one scalar variable. Data sets were drawn from three scientific domains: Landsat, medical MRI, and global atmospheric data bases. Two types of features were embedded within the data sets: circular (blob-like) discontinuities, and linear (cliff-like) discontinuities. Results showed a general advantage for the gray scale, and a marked disadvantage for the 3D-topographic format in both accuracy and response latency. Performance in the two color scale formats was intermediate, with the reduced hue scale supporting faster, if not more accurate performance than the full rainbow scale. Performance differences were found across data base domains, as well. Directions for future research are discussed.

Milgram, P., D. Drascic and J. J. Grodski (1991). Enhancement of 3-D Video Displays by Means of Superimposed Stereo-Graphics. Proceedings of the Human Factors Society 35th Annual Meeting 1457-1461
[Structural Integrity: Depth Cues].

This paper describes a number of aspects of a display technology under development, which involves the integration of stereoscopic computer graphics and stereoscopic video displays. The background and justification for this development are discussed, based on the need of operators of remotely controlled vehicles and/or manipulators to estimate absolute sizes and locations of objects at a remotely viewed site. The basic technology involves superimposing an interactively controllable computer-generated stereographic cursor onto a stereoscopically viewed video image. Absolute measurements can be made with this system, based on relative comparison of cursor position with target object location. Experimental results are presented in which the ability of subjects to perform such tasks was investigated. In general, results were promising; subjects were able to align virtual pointers with real targets essentially as well as they were able to manipulate real objects. A number of implications of this technology for the enhancement of three dimensional video displays are discussed.

Nemire, K., R. H. Jacoby and S. R. Ellis (1994). “Simulation fidelity of a virtual environment display.” Human Factors **36**(1): 79-93
[Structural Integrity: Depth Cues, Situation].

Assessed the degree to which a virtual environment system produced a faithful simulation of 3-dimensional space by investigating the influence of a pitched optic array (POA) on the perception of gravity-referenced eye level (GREL). The results were compared with those obtained in a physical environment. In a within-Ss factorial design, 12 college students (aged 18-51 yrs) indicated GREL while viewing virtual 3-dimensional arrays at different static orientations. Results replicate those obtained with a physical pitched box (e.g., M. M. Cohen and

C. Ballinger, 1989) in demonstrating that GREL is influenced by the pitch of the optic environment. They demonstrate that the magnitude of the influence of a POA on GREL changes as a function of the structure of the pitched environment. An additional optic structure was necessary for the pitched virtual box to influence GREL as much as the geometrically similar pitched physical box. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

Sollenberger, R. L. and P. Milgram (1991). A Comparative Study of Rotational and Stereoscopic Computer Graphic Depth Cues. Proceedings of the Human Factors Society 35th Annual Meeting 1452-1456
[Structural Integrity: Depth Cues].

The present research investigated the effectiveness of rotational and stereoscopic display techniques as applied to practical applications in computer graphics. In the described experiments, depth perception was evaluated by examining accuracy in a 3D path-tracing task, with stimulus displays resembling the structure of cerebral angiograms. In the first experiment, task performance was determined without 3D enhancements, with either technique used alone and with both techniques combined. The results indicated that performance improved using either technique, however, performance with rotational displays was superior to stereoscopic displays, and performance was best when both techniques were combined. The results of a second experiment revealed that rotational displays were no better than stereoscopic displays enhanced with multiple static viewing angles. The experimental findings are discussed in terms of the visual information available using either 3D display technique as well as with respect to the hardware requirements of both display systems. The results are also related to the weighted additive model of depth perception.

Takemura, H., A. Tomono and Y. Kobayashi (1989). A Study of Human-Computer Interaction Via Stereoscopic Display. Proceedings of the Third International Conference on Human-Computer Interaction 496-503
[Structural Integrity: Depth Cues].

By combining a stereoscopic display and appropriate input devices, a new man-machine interface can be designed. Discussed in this paper are problems to be solved in order to realize this environment, including a high fidelity display method for stereoscopic displays and man-machine interface technique for 3-D image manipulation. We have constructed a display system which determines the position of the viewer's eye and generates an image based on his/her actual viewpoint. We have also evaluated the fidelity of the image displayed. As a test of a 3-D image manipulating interface, we evaluated the task of locating a 3-D cursor at the target position of the stereoscopic display using three types of input devices: dial-box, mouse and 3-D digitizer, with from one to three degrees of freedom.

Utsumi, A., P. Milgram, H. Takemura and F. Kishino (1994). Investigation of Errors in Perception of Stereoscopically Presented Virtual Object Locations in Real Display Space. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 250-254
[Structural Integrity: Depth Cues].

This paper describes studies on perception of virtual object locations. It explores the behavior of some factors related to depth perception, especially the effect of inter-pupillary distance (IPD) mismatch and the interplay of image blur and binocular disparity. IPD mismatch (which is caused by errors in estimation of the parameter) results in a certain perceptual error of virtual objects' depth. Blur of images is also a source of error in depth representation. It was found, in some cases, to be a very strong depth cue. The results of a series of experiments conducted on IPD mismatch and image blur are also presented.

Waldern, J. D., A. Humrich and L. Cochrane (1986). "Studying Depth Cues in a Three-Dimensional Computer Graphics Workstation." International Journal of Man-Machine Studies **24**(6): 645-657
[Identifiability: Dimensionality, Structural Integrity: Depth Cues].

A Three-Dimensional Interactive Graphics Workstation has been constructed within the Human-Computer Interface Research Unit. The principal accomplishment of this workstation has been to provide a tool enabling a user to interact with a computer-generated image perceived in three dimensions. This image is perceived by workstation users to exist in free space forward of a VDU screen. A pilot experiment has been conducted where subjects interact both with a simple model of a cube and a three-dimensional computer-generated representation of the cube. The results indicate a significant positive correlation between performances using the cube model and the 3-D representation.

Ware, C. (1995). Dynamic Stereo Displays. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 310-316
[Structural Integrity: Depth Cues].

Based on a review of the facts about human stereo vision, a case is made that the stereo processing mechanism is highly flexible. Stereopsis seems to provide only local additional depth information, rather than defining the overall 3D geometry of a perceived scene. New phenomenological and experimental evidence is presented to support this view. The first demonstration shows that kinetic depth information dominates stereopsis in a depth cue conflict. Experiment 1 shows that dynamic changes in effective eye separation are not noticed if they occur over a period of a few seconds. Experiment 2 shows that subjects who are given control over their effective eye separation, can comfortably work with larger than normal eye separations when viewing a low relief scene. Finally, an algorithm is presented for the generation of dynamic stereo images designed to reduce the normal eye strain that occurs due to the mis-coupling of focus and vergence cues.

Ware, C., K. Arthur and K. S. Booth (1993). Fish Tank Virtual Reality. Proceedings of ACM INTERCHI'93 Conference on Human Factors in Computing Systems 37-42
[Structural Integrity: Depth Cues].

The defining characteristics of what we call "Fish Tank Virtual Reality" are a stereo image of a three dimensional (3D) scene viewed on a monitor using a perspective projection coupled to the head position of the observer. We discuss some of the relative merits of this mode of viewing as compared to head mounted stereo displays. In addition, we report the experimental investigation of the following variables: 1) whether or not the perspective view is coupled to the actual viewpoint of the observer, 2) whether stereopsis is employed. Experiment 1 involved the subjective comparison of pairs of viewing conditions and the results suggest that head coupling may be more important than stereo in yielding a strong impression of three dimensionality.

Experiment 2 involved subjects tracing a path from a leaf of a 3D tree to the correct root (there were two trees intermeshed). The error rates ranged from 22% in the pictorial display, to 1.3% in the head coupled stereo display. The error rates for stereo alone and head coupling alone were 14.7% and 3.2% respectively. We conclude that head coupling is probably more important than stereo in 3D visualization and that head coupling and stereo combined provide an important enhancement to monitor based computer graphics.

Woodrow, B. and K. Young (1991). Computer Graphics Programming Principals as Factors in the Design of Perspective Displays. Proceedings of the Fourth International Conference on Human-Computer Interaction 93-97
[Structural Integrity: Depth Cues].

An important issue in the design of perspective displays concerns the relationship between the perspective geometry parameters used to design such displays and the accuracy with which observers can reconstruct the spatial information contained within the perspective projection. These are important issues for the design of visual displays because viewing a three-dimensional (3D) image projected onto a two-dimensional (2D) surface requires that the observer mentally reconstruct the original 3D information based on the perspective projection. There are several geometric parameters of perspective which influence the accuracy with which observers can reconstruct the original 3D information (McGreevy and Ellis, 1986). These include the geometric field of view (GFOV) and station point distance. This study investigated the effect of these variables on the accuracy of an exocentric direction task using a computer-generated perspective display.

B. Developing and Executing Action Sequences: Enable the user to achieve goals, perform tasks, and execute commands easily.

B.1. Sequential Clarity and Simplicity: Make procedural sequences clear and simple.

Navigation

Arents, H. C. and W. F. L. Bogaerts (1993). "Navigation Without Links and Nodes Without Contents: Intensional Navigation in a Third-Order Hypermedia System." Hypermedia 5(3): 187-204
[Structural Integrity, Sequential Clarity: Navigation].

The key to unlocking the navigation potential of hypertext and hypermedia systems lies in a more semantics-aware indexing of the interrelated information stored in these systems. We first highlight briefly the different indexing techniques which have been proposed for hypertext and hypermedia systems, and we then discuss the so-called semantic hyperindexing technique which we have recently developed to represent the significant relations between hypertextual information. We discuss in detail how this technique is being used to support intensional navigation in a third-order hypermedia system, based on the definition of meaningful traversal trails between semantically associated nodes, which the reader can navigate freely at his own discretion while still being gently guided by the system. Finally, we consider the graphical notation which we have developed to help the authors in visualizing these intensionally defined traversal trails, and we discuss how the use of this notation improves the productiveness of the authors during trail design.

Aretz, A. J. and C. D. Wickens (1992). "The mental rotation of map displays." Human Performance 5(4): 303-328
[Structural Integrity, Sequential Clarity: Navigation].

Two experiments investigated the cognitive processes used during map reading by 24 male undergraduates. The hypothesis examined was that localization using a map is the product of a cognitive alignment between 2 frames of reference. The ego-centered reference frame corresponds to the forward perceptual view of the world, whereas the world-centered reference frame corresponds to a location on the map. The data suggest that mental rotation is involved in the alignment in a 2-step process. Although mental rotation may be generalized outside the laboratory to navigation tasks, the data also suggest that when the rotation becomes too complex, a more analytic approach is used.

Bartram, L., A. Ho, J. Dill and F. Henigman (1995). The Continuous Zoom: A Constrained Fisheye Technique for Viewing and Navigating Large Information Spaces. Proceedings of the ACM Symposium on User Interface Software and Technology 207-215
[Sequential Clarity: Navigation].

Navigating and viewing large information spaces, such as hierarchically-organized networks from complex real-time systems, suffer the problems of viewing a large space on a small screen. Distorted-view approaches, such as fisheye techniques, have great potential to reduce these problems by representing detail within its larger context but introduce new issues of focus, transition between views and user disorientation from excessive distortion. We present a fisheye-based method which supports multiple focus points, enhances continuity through smooth transitions between views, and maintains location constraints to reduce the user's sense of spatial disorientation. These are important requirements for the representation and navigation of networked systems in supervisory control applications. The method consists of two steps: a global allocation of space to rectangular sections of the display, based on scale factors, followed by degree-of-interest adjustments. Previous versions of the algorithm relied solely on relative scale factors to assign size; we present a new version which allocates space more efficiently using a dynamically calculated degree of interest. In addition to the automatic system sizing, manual user control over the amount of space assigned each area is supported. The amount of detail shown in various parts of the network is controlled by pruning the hierarchy and presenting those sections in summary form.

Dieberger, A. (1993). The Information City -- A Step towards Merging of Hypertext and Virtual Reality. Proceedings of ACM Hypertext'93 -- Posters 30
[Visibility, Sequential Clarity: Navigation, Familiarity].

The Information-City is a three dimensional user interface for large hypertext collections. It uses the metaphor of a city to represent documents as buildings in a virtual environment the user navigates and makes heavy use of Jay Bolter's "writing on the world" concept to visualize as much information about the documents as possible without overloading the user (e.g. age, relevancy, accessibility). The city is restructured according to user interest profile and document similarity to create "districts of interest". The city metaphor shall help the user to build a conceptual map of the environment. As autonomous actor the system helps the user to locate information by providing light cues and transportation (taxi and subway metaphors). Significant information is pointed out by open doors for instance. Visualization of hypertext nets as house structures is done using hypertext abstractions, so called building blocks. These constructs define a hierarchical subset of the hypertext web that can be visualized different than the rest of the web -- namely as halls and rooms. A second, purely textual version of the information city is constructed in a MUD (Multi User Dungeon) system and will be available on the internet. This system is used to study collaborative navigational behaviour in a multi user environment (development of landmarks and navigation paths). Findings of this version will be used to improve the graphical version of the information city. At the time of writing an authoring tool using building blocks is under construction.

Furnas, G. W. and B. B. Bederson (1995). Space-Scale Diagrams: Understanding Multiscale Interfaces. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 234-241
[Sequential Clarity: Navigation, Familiarity].

Big information worlds cause big problems for interfaces. There is too much to see. They are hard to navigate. An armada of techniques has been proposed to present the many scales of information needed. Space-scale diagrams provide an analytic framework for much of this work. By representing both a spatial world and its different magnifications explicitly, the diagrams allow the direct visualization and analysis of important scale related issues for interfaces.

Kordell, G. J. and M. M. Sebrechts (1993). Icon and Diagram Use in Data Navigation: I Know I'm There, but Where is That. Proceedings of ACM Hypertext'93 -- Posters 28

[Sequential Clarity: Navigation].

A popular instructional hypermedia system about conflict in the Middle East was used to test the hypothesis that diagrammatic information can improve hyperspace navigation. Three variants of the system provided alternative access to a fixed database. In the first "icon map" condition subjects used icons to access four high-level divisions of the database (history timeline, religion, geography, and bibliographic and documentary resources). The second "static schematic" condition augmented the icon map by displaying a static diagram of the database, including all major nodes and links. The final "active schematic" condition included an active version of the static schematic; subjects could access any node by selecting it directly from the diagram. Forty-two students spent approximately one hour using one of the three variants of the system to answer questions about the Middle East. Regardless of condition, the optimal strategy appeared to consist of an initial browsing phase followed by specific search. Subjects who failed to go through an overview of the materials often encountered the relevant data, but failed to include it in their summary report. Available diagrams were often ignored or misused. Content knowledge was far more important than knowledge about the structure of the database in setting expectations about information location. Navigating mental space may be very different from navigating a data space. This perspective gives some legitimacy to the seemingly paradoxical claim, "I know where I am but where is that."

Lieberman, H. (1994). Powers of Ten Thousand: Navigating in Large Information Spaces. Proceedings of the ACM Symposium on User Interface Software and Technology 15-16
[Sequential Clarity: Navigation, Familiarity].

How would you interactively browse a very large display space, for example, a street map of the entire United States? The traditional solution is zoom and pan. But each time a zoom-in operation takes place, the context from which it came is visually lost. Sequential applications of the zoom-in and zoom-out operations may become tedious. This paper proposes an alternative technique, the microscope, based on zooming and panning in multiple translucent layers. A microscope display should comfortably permit browsing continuously on a single image, or set of images in multiple resolutions, on a scale of at least 1 to 10,000.

Masuda, Y., Y. Ishitobi and M. Ueda (1994). Frame-Axis Model for Automatic Information Organizing and Spatial Navigation. Proceedings of the ECHT'94 European Conference on Hypermedia Technologies 146-157
[Sequential Clarity: Navigation, Traceability].

In taxonomic reasoning tasks, such as scientific research or decision making, people gain insight and find new ideas through analysis of large numbers of factual data or material documents, which are generally disorganized and unstructured. Hypermedia technology provides effective means of organizing and browsing information with such nature. However, for large amounts of information, the conventional node-link model makes linking or browsing operations be complicated because their relationship have to be represented as binary relations. In this paper, we propose a hypermedia data model call Frame-Axis Model, which represents relationship between information as N-ary relations on mapped space. Also, the automatic information organizing mechanism which is based on this data model and the browsing interface HyperCharts which employ spatial layout are provided. Finally, we show some browsing examples on our working prototype system, CastingNet.

Mukherjea, S., J. D. Foley and S. E. Hudson (1994). Interactive Clustering for Navigating in Hypermedia Systems. Proceedings of the ECHT'94 European Conference on Hypermedia Technologies 136-145
[Visibility, Identifiability: Perceptual Grouping, Sequential Clarity: Navigation, Familiarity].

This paper talks about clustering related nodes of an overview diagram to reduce its complexity and size. This is because although overview diagrams are useful for helping the user to navigate in a hypermedia system, for any real-world system these become too complicated and large to be really useful. Both structure-based and content-based clustering are used. Since the nodes can be related to each other in different ways, depending on the situation different clustered views will be useful. Hence, it should be possible to interactively specify the clustering conditions and examine the resulting views. We present efficient clustering algorithms which can cluster the information space in real-time. We talk about the Navigational View Builder, a tool that allows the interactive development of overview diagrams. Finally, we propose a 3-dimensional approach for visualizing these abstracted views.

Rouet, J.-F. (1992). Cognitive Processing of Hyperdocuments: When Does Nonlinearity Help? Proceedings of the Fourth ACM Conference on Hypertext 131-140
[Sequential Clarity: Navigation, Structural Integrity].

This paper presents a review of empirical research on the cognitive processing of nonlinear documents, with the purpose of understanding when and how hypertext presentation might facilitate text comprehension and learning activities. Empirical studies conducted so far have used various methods, and focused on a wide range of populations, types of documents, and reading or learning tasks. Although hypertext is generally associated with information networks, a few interesting studies address the issues of computer assistance to linear text comprehension. A second group of studies investigate the use of nonlinear documents for general learning purposes. Although these studies are mainly concerned with linear-nonlinear comparisons, some of them address the effects of different design options. Finally, a third group of studies compare information retrieval in linear versus nonlinear documents. Overall, there is no consistent evidence for the advantage of hypertext over linear presentation formats. Instead, the efficiency of nonlinear documents varies according to (a) subjects' expertise (b) interface features and (c) task requirements. In an attempt to provide an interpretative framework for these empirical findings, the notion of cognitive monitoring is briefly outlined. I conclude with a few implications for future hypertext research.

Sheelagh, M., T. Carpendale, J. C. David and F. D. Fracchia (1995). 3-Dimensional Pliable Surfaces: For the Effective Presentation of Visual Information. Proceedings of the ACM Symposium on User Interface Software and Technology 217-226
[Sequential Clarity: Navigation].

A fundamental issue in user interface design is the effective use of available screen space, commonly referred to as the screen real estate problem. This paper presents a new distortion-based viewing tool for exploring large information spaces through the use of a three-dimensional pliable surface. Arbitrarily-shaped regions (foci) on the surface may be selected and pulled towards or pushed away from the viewer thereby increasing or decreasing the level of detail contained within each region. Furthermore, multiple foci are smoothly blended together such that there is no loss of context. The manipulation and blending of foci is accomplished using a fairly simple mathematical model based on gaussian curves. The significance of this approach is that it utilizes precognitive perceptual cues about the three-dimensional surface to make the distortions comprehensible, and allows the user to interactively control the location, shape, and extent of the distortion in very large graphs or maps.

Spence, R. and M. Apperley (1982). " Data Base Navigation: An Office Environment for the Professional." Behavior and Information Technology **1**(1): 43-54
[Sequential Clarity: Navigation].

The potential of the computer to assist in the everyday information handling activities of professional people has received little attention. This paper proposes a number of novel facilities to produce, for his purpose, an office environment in which needed item of information can rapidly be sought and identified. It involves a new display technique which overcomes the classical "windowing" problem, and the use of natural dialogues utilizing simple actions such as pointing, gesturing, touching and spoken commands. The simple dialogue makes the scheme well suited to the professional person, who is most likely unwilling to learn complex command languages. Little disturbances to the appearance of the office need be involved.

Thorndyke, P. W. and B. Hayes Roth (1982). "Differences in spatial knowledge acquired from maps and navigation." Cognitive Psychology **14**(4): 560-589
[Cognition and Perception, Sequential Clarity: Navigation].

Proposes models of the spatial knowledge acquired from maps and navigation and the procedures required for spatial judgments using this knowledge. From a map, people acquire survey knowledge encoding global spatial relations. This knowledge resides in memory in images that can be scanned and measured like a physical map. From navigation, people acquire procedural knowledge of the routes connecting diverse locations and combine mental simulation of travel through the environment and informal algebra to compute spatial judgments. An experiment in which 48 female employees and college students learned an environment from navigation or from a map evaluated predictions of these models. With moderate exposure, map learning was superior for judgments of relative location and straight-line distances among objects. Learning from navigation was superior when Ss oriented themselves with respect to unseen objects and estimated route distances. With extensive exposure, the performance superiority of maps over navigation vanished. Results are consonant with the proposed mechanisms. (36 ref) (PsycLIT Database Copyright 1983 American Psychological Assn, all rights reserved)

Tolsby, H. (1993). Navigating in a Process Landscape. East-West International Conference on Human-Computer Interaction: Proceedings of the EWHCI'93 26-38
[Sequential Clarity: Navigation, Familiarity].

User interfaces in process control systems are often organized as landscapes -- usually a process chart -- where the display is a window into the landscape. The window can move over the landscape and view different segments of the process. Normally there is no overlap between the views -- they are discretely organized. Operators often claim they get lost in such interfaces. It is suggested that the problem is a matter of how the operator moves in the landscape -- how one changes ones view of the process. Two different interactive methods of movement -- discrete vs. continuous -- are tested. The results of the experiments are discussed.

Wickens, C. D., C.-C. Liang, T. Prevett and O. Olmos (1994). Egocentric and Exocentric Displays for Terminal Area Navigation. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 16-20
[Sequential Clarity: Navigation].

Two experiments are reported that contrast egocentric vs. exocentric features of perspective (3D) or plan view (2D) electronic map displays for supporting local guidance and global awareness. Pilots used these displays for a simulated approach to a landing along a curved approach, through a terrain-filled region. The task was simulated on an IRIS visual graphics workstation. In Experiment 1, a rotating vs. fixed-map display was experimentally crossed with a 2D vs. 3D (perspective map) view as 24 pilots were assessed in their ability to maintain the flight path (local guidance) and demonstrate global awareness of surrounding terrain features. Rotating displays supported better flight path guidance in both the lateral and vertical axes, and did not substantially harm performance on the task of recalling the location of terrain features. Map rotation also supported better performance in locating features from an ego-referenced but not a world-referenced perspective. 3D displays provided a slight advantage for lateral guidance but a substantial cost for vertical control, because of the ambiguity with which perspective viewing depicted precise altitude. In Experiment 2, 10 pilots flew with the rotating 2D display, and with an improved version of the rotating 3D display, using color coding to reduce the ambiguity of altitude information. Vertical control improved as a result of the 3D display design improvement, but lateral control did not. Assessment of terrain awareness on a map reconstruction task revealed marginally better performance with the 2D map. The results are discussed in terms of the costs and benefits of presenting information in 3D, ego-referenced format for both local guidance and global awareness tasks.

Wilkins, R. J. and M. J. Weal (1993). VirtualMedia: Virtual Reality as a Hypermedia Navigation Tool. Proceedings of ACM Hypertext'93 -- Posters 23
[Sequential Clarity: Navigation, Familiarity].

It is well known that navigation within existing hypermedia can be difficult. As the size and complexity of hypermedia increases such navigation problems will become more apparent. It is essential to provide the user with tools that enable them to maintain their spatial awareness. The desktop metaphor and the tools within do not readily present the user with the spatial and structural relationships which may exist within hypermedia. A new virtual space metaphor will provide the user with a consistent visual representation of any such structures. We have currently implemented two hypermedia applications which provide the user with a virtual space representations of the data and the relationships between that data. Both applications use Autocad to manipulate the virtual spaces and have been authored within the Microcosm open hypermedia system. The first application contains data about Bath (an English town). Links exist between a 3D model of the buildings and other data (photographs, descriptive text and rendered images/animations). The user can immediately see the spatial relationships between the buildings in the model and hence the other data in the system. The second application contains maintenance manuals for a cable packaging machine owned by Pirelli. The user locates a part of the machine in the 3D model and follows links to the relevant maintenance information. These two applications lead us to believe that such a spatial representation would benefit other, perhaps non-inherently spatial, hypermedia documents. A tool for producing and using such a generalised virtual space is the main subject of the poster.

B.2. Input Compatibility: Provide intuitive, natural mapping between input devices, the visual interface, and the user's task.

Allport, D., E. Rennison and L. Strausfeld (1995). Issues of Gestural Navigation in Abstract Information Spaces. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 206-207
[Input Compatibility, Sequential Clarity: Navigation].

Navigating large multidimensional information spaces presents a set of unique problems for user interface design. The key challenge is not to provide fast and accurate object manipulation, but to prevent the user from getting "lost", and to provide an intuitive way to move through the space. We have developed an interface that uses electrostatic field sensing to interpret natural hand gestures as motion controllers. We are investigating the conceptual models that provide intuitive mappings from hand gestures to movements in multidimensional information space.

Andries van, D., K. P. Herndon and M. Gleicher (1994). The Challenges of 3D Interaction. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 469
[Input Compatibility, Evaluation].

The primary goal of this workshop is to help define principles and techniques for the design, implementation and evaluation of future 3D user interfaces. These interfaces must address many challenges arising from such sources as users' perceptual and cognitive skills and abilities, limitations of currently available input and output devices, the nature of 3D tasks and the variety of implementation strategies and development environments.

Barthelemy, K. K., J. M. Reising and D. C. Hartsock (1991). Target Designation in a Perspective View, 3-D Map Using a Joystick, Hand Tracker, or Voice. Proceedings of the Human Factors Society 35th Annual Meeting 97-101
[Input Compatibility].

The purpose of this study was to determine which of three cursor control techniques would provide the best means of designating targets in three-dimensional space. The three techniques tested were a joystick, a hand tracker, and voice. The current study showed that the quickest and most accurate target designations occurred when using the hand tracker, and when targets were positioned in the front most part of the three-dimensional volume.

Bauer, W. and O. Riedel (1993). New Techniques for Interaction in Virtual Worlds -- Contents of Development and Examples. Proceedings of the Fifth International Conference on Human-Computer Interaction 687-692
[Input Compatibility].

A number of industrial applications of Virtual Reality have recently appeared on the market which are no longer toys but real tools. Multidimensional input devices like the Spacebar, the Spacemouse, or the DataGlove are available and provide the users with intuitive three-dimensional interaction capabilities. But what about the ergonomic software interface for the user of VR? The most common interface to virtual worlds -- a glove -- is not sufficiently accurate to ensure that all gestures necessary for the handling of a complex program can be measured. As a result, the user must spend a great deal of time becoming familiar with the complex worlds and learning to use the interface effectively and efficiently. This paper will discuss a 3-D user interface to virtual worlds which is similar to the well-known 2-D GUI's, but which is driven not only by gestures, but by a combination of gestures and icons.

Boyd, C. (1995). Human and Machine Dimensions of 3D Interfaces for Virtual Environments. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 41-42
[Input Compatibility: Navigation, Evaluation].

This work explores two categories for evaluating and measuring virtual environment (VE) interfaces. One category concerns characteristics of the interface, such as its complexity and abstractness. The other category concerns the human capacities for understanding and using three-dimensional input/output devices. The results may help us predict the usability of VE interfaces and help us to design interfaces that are well matched to their intended users.

Hinckley, K., R. Pausch, J. C. Goble and N. F. Kassell (1994). A Survey of Design Issues in Spatial Input. Proceedings of the ACM Symposium on User Interface Software and Technology 213-222
[Input Compatibility, Evaluation].

We present a survey of design issues for developing effective free-space three-dimensional (3D) user interfaces. Our survey is based upon previous work in 3D interaction, our experience in developing free-space interfaces, and our informal observations of test users. We illustrate our design issues using examples drawn from instances of 3D interfaces. For example, our first issue suggests that users have difficulty understanding three-dimensional space. We offer a set of strategies which may help users to better perceive a 3D virtual environment, including the use of spatial references, relative gesture, two-handed interaction, multisensory feedback, physical constraints, and head tracking. We describe interfaces which employ these strategies. Our major contribution is the synthesis of many scattered results, observations, and examples into a common framework. This framework should serve as a guide to researchers or systems builders who may not be familiar with design issues in spatial input. Where appropriate, we also try to identify areas in free-space 3D interaction which we see as likely candidates for additional research. An extended and annotated version of the references list for this paper is available on-line through mosaic at address http://uvacs.cs.virginia.edu/~kph2q/.

James, B. S. (1993). Cognitive Performance of Individuals Using a Head-Mounted Display while Walking. Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting 338-342
[Input Compatibility].

Considerable research has been conducted on head or helmet-mounted displays (HMDs) for aviators, but little, if any, for ground soldiers. This study investigated the ability of individuals to perform combined tasks of walking over irregular terrain (simulated) and processing information from an HMD. Volunteers performed reaction time tasks while either standing or walking on a treadmill, with and without obstacles. Results show uniform effects of obstacles on three levels of cognitive difficulty. Walking on level ground with no obstacles had no more effect on information processing than merely standing, whereas minor and moderate levels of obstacle avoidance had equal impact. Spatial displays were easier than verbal and numeric displays during all levels of mobility. Subjective effort matched reaction time performance. Results support existing models of attention and will help provide guidance for unique applications for the ground combatant.

Mackinlay, J., S. K. Card and G. G. Robertson (1990). "A Semantic Analysis of the Design Space of Input Devices." Human-Computer Interaction 5(2-3): 145-190
[Input Compatibility].

A bewildering variety of devices for communication from humans to computers now exists on the market. In this article, we propose a descriptive framework for analyzing the design space of these input devices. We begin with Buxton's (1983) idea that input devices are transducers of physical properties into one, two, or three dimensions. Following Mackinlay's semantic analysis of the design space for graphical presentations, we extend this idea to more comprehensive descriptions of physical properties, space, and transducer mappings. In our reformulation, input devices are transducers of any combination of linear and rotary, absolute and relative, position and force, in any of the six spatial degrees of freedom. Simple input devices are described in terms of semantic mappings from the transducers of physical properties into the parameters of the applications. One of these mappings, the resolution function, allows us to describe the range of possibilities from continuous devices to discrete devices, including possibilities in between. Complex input controls are described in terms of hierarchical families of generic devices and in terms of composition operators on simpler devices. The description that emerges is used to produce a new taxonomy of input devices. The taxonomy is compared with previous taxonomies of Foley, Wallace, and Chan (1984) and of Buxton (1983) by reclassifying the devices previously analyzed by these authors. The descriptive techniques are further applied to the design of complex mouse-based virtual input controls for simulated three-dimensional (3D) egocentric motion. One result is the design of a new virtual egocentric motion control.

Murakami, T., K. Hayashi, K. Oikawa and N. Nakajima (1995). DO-IT: Deformable Objects as Input Tools. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 87-88
[Input Compatibility, Example].

Standard input tools such as the mouse and keyboard do not provide users with a direct and intuitive means of 3-D shape manipulation. This study proposes a new concept of interface system for 3-D shape deformation using a deformable real object as an input tool. By deforming the tool with bare hands with a tactile feedback, users can manipulate a 3-D shape modeled and displayed on a computer screen directly and intuitively. A PC-based prototype system with a cubical input tool made of electrically conductive polyurethane foam demonstrates the effectiveness and promise of the concept.

Murakami, T. and N. Nakajima (1994). Direct and Intuitive Input Device for 3-D Shape Deformation. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 233
[Input Compatibility, Familiarity].

Standard input devices such as a mouse and a keyboard in present computer-aided design systems do not provide users with direct and intuitive facilities for highly 3-D shape manipulation. To solve the problem, this paper proposes a new interface system for 3-D shape manipulation by adopting a real elastic object as an input device. By deforming the device with bare hands with a tactile feedback, users can manipulate a 3-D shape modeled and displayed on a computer screen quite directly and intuitively. A prototype with a cubical input device made of electrically conductive polyurethane foam is also presented.

Nesi, P. and A. D. Bimbo (1996). "A Vision-Based 3-D Mouse." International Journal of Human-Computer Studies **44**(1): 73-91
[Identifiability, Input Compatibility,].

Recently, several devices for improving quality and efficiency human-computer interaction have been proposed. This is mainly due to the requirements of virtual reality applications, where the greatest part of the most circulating devices must be worn by the user -- e.g. gloves for hand-tracking, complete or partial tracksuits. These techniques allow the estimation of most human body movements. On the other hand, the adoption of such devices is unsuitable for many applications since they are too constrictive -- e.g. teleconferencing. For this reason, other simpler devices such as 3-D mice have been suggested. Most of the 3-D mice proposed in the literature compel the user to be connected to the device and their behaviour is much closer to a Joystick rather than to a true 3-D mouse. More recently, vision-based hand tracking systems have been presented, but most of them constrain the user to wear gloves, bracelets or to mark some points on the hand. In this paper, a vision-based, glove- and mark-free hand tracking system is proposed. This is based on stereo vision and can be implemented with low-cost architectures owing to its low computational complexity. In addition, the estimation process defined is very robust and allows the simultaneous hand-position tracking and the recognition of some hand postures, thus implementing a true non-constrictive 3-D mouse.

Schryver, J. C. and J. H. Goldberg (1993). Eye-Gaze and Intent: Application in 3D Interface Control. Proceedings of the Fifth International Conference on Human-Computer Interaction 573-578
[Input Compatibility].

Computer interface control is typically accomplished with an input "device" such as keyboard, mouse, trackball, etc. An input device translates a user's input actions, such as mouse clicks and key presses, into appropriate computer commands. To control the interface, the user must first convert intent into the syntax of the input device. A more natural means of computer control is possible when the computer can directly infer user intent, without need of intervening input devices. We describe an application of eye-gaze-contingent control of an interactive three-dimensional (3D) user interface. A salient feature of the user interface is natural input, with a heightened impression of controlling the computer directly by the mind. With this interface, input of rotation and translation are intuitive, whereas other abstract features, such as zoom, are more problematic to match with user intent. This paper describes successes with implementation to date, and ongoing efforts to develop a more sophisticated intent inferencing methodology.

Shaw, C. and M. Green (1994). Two-Handed Polygonal Surface Design. Proceedings of the ACM Symposium on User Interface Software and Technology 205-212
[Input Compatibility, Example].

This paper describes a Computer Aided Design system for sketching free-form polygonal surfaces such as terrains and other natural objects. The user manipulates two 3D position and orientation trackers with three buttons, one for each hand. Each hand has a distinct role to play, with the dominant hand being responsible for picking and manipulation, and the less-dominant hand being responsible for context setting of various kinds. The less-dominant hand holds the workpiece, sets which refinement level that can be picked by the dominant hand, and generally acts as a counterpoint to the dominant hand. In this paper, the architecture of the system is outlined, and a simple surface is shown.

Solz, T. J., J. M. Reising, K. K. Liggett, T. Lohmeyer and D. C. Hartsock (1994). The Use of Aiding Techniques and Varying Depth Volumes to Designate Targets in 3-D Space. Proceedings of the Human Factors and Ergonomics Society 38th Annual Meeting 1-5
[Identifiability: Interaction Techniques, Input Compatibility].

The purpose of this study was to determine the effectiveness of a hand tracker to designate targets using a three-dimensional (3-D) map. Three variables were manipulated: 1) hand tracker active volume, 2) aiding technique, and 3) target density. There were three different volumes (large, medium and small) in which the hand tracker operated. Each volume represented cockpit space in which hand tracker movements correlated to cursor movements on the screen. Two aiding techniques were referred to as contact aiding and proximity aiding. Contact aiding consisted of a color shade change to the target when the cursor penetrated the target volume. Proximity aiding consisted of an algorithm that selected the target closest to the cursor and thus changed its color shade. Two target densities, high (16 targets) and low (8 targets), were used. Speed and accuracy were measured in the designation of targets using a hand tracker. Results showed that proximity aiding in the medium volume space yielded the best performance.

Venolia, D. (1993). Facile 3D Direct Manipulation. Proceedings of ACM INTERCHI'93 Conference on Human Factors in Computing Systems 31-36
[Visibility, Identifiability, Input Compatibility].

An experimental 3D interface is described, including rendering acceleration hardware, a 3D mouse, and 3D interaction techniques. A 3D cursor, controlled by the augmented mouse, allows direct manipulation of 3D objects. Objects are selected by placing the tip of the cursor inside. Objects can be moved in 3D, or simultaneously moved and rotated using a technique called "tail-dragging." A method called "snap-to" helps users align objects. The interface is designed without using explicit modes or commands. Sounds accentuate the interaction. Details of the implementation and informal user observations are described, as well as topics for future work.

Wloka, M. M. and E. Greenfield (1995). The Virtual Tricorder: A Uniform Interface for Virtual Reality, Proceedings of the ACM Symposium on User Interface Software and Technology 39-40
[Visibility, Familiarity].

We describe a new user-interface metaphor for immersive virtual reality -- the virtual tricorder. The virtual tricorder visually duplicates a six-degrees-of-freedom input device in the virtual environment. Since we map the input device to the tricorder one-to-one at all times, the user identifies the two. Thus, the resulting interface is visual as well as tactile, multipurpose, and based on a tool metaphor. It unifies many existing interaction techniques for immersive virtual reality.

B.3. Traceability, Recoverability and Resilience: Provide a means to retrieve previously used sequences or information, recover from unintended or incorrect actions, and assist users in avoiding results from which they cannot recover.

Charles, S. and S. Scrivener (1990). "Using depictive queries to search pictorial databases." In Proceedings of IFIP INTERACT '90: Human Computer Interaction: 493-498
[Visibility, Traceability].

This paper argues that pictorial databases are becoming, and will continue to be, important in information systems because pictures can be used to depict information which is difficult to describe or perhaps incomprehensible in non-pictorial form. It follows that when searching for a picture the user might find it easier to depict the query by means of a picture. This paper describes a method for searching pictorial databases where the user essentially constructs a sketch (which combines depiction and description) of the target picture.

Greenberg, S. and I. H. Witten (1988). How users repeat their actions on computers: principles for design of history mechanisms. In Proceedings of ACM CHI'88 Conference on Human Factors in Computing Systems 171-178
[Traceability].

Several striking characteristics of how often people repeat their actions on interactive systems are abstracted from usage data gleaned from many users of different classes over a period of months. Reformulated as empirically-based general principles, these provide design guidelines for history mechanisms specifically and modern user interfaces generally. Particular attention is paid to the repetition of command lines, and to the probability distribution of the next line given a sequential "history list" of previous ones. Several ways are examined of conditioning this distribution to enhance predictive power. A brief case study of actual use of a widely-used history system is also included.

Greenberg, S. and I. H. Witten (1993). "Supporting command reuse: Mechanisms for reuse." Internationa Journal of Man Machine Studies **39**(3): 391-425
[Traceability].

Reuse facilities help people to recall and modify their earlier activities and resubmit them to the computer. Guidelines for building reuse facilities are summarized. Existing reuse facilities are surveyed under 4 main headings: history mechanisms, adaptive systems, programming by example, and explicit customization. A reuse facility that uses an empirically derived history system as a way of capturing and organizing one's situated activities is described. An appendix reports a study of a history system and explains why it is poorly used in practice. 168 novice programmers, experienced programmers, computer scientists, and nonprogrammers were studied using the system over a 4-mo. period. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved).

Masuda, Y., Y. Ishitobi and M. Ueda (1994). Frame-Axis Model for Automatic Information Organizing and Spatial Navigation. Proceedings of the ECHT'94 European Conference on Hypermedia Technologies 146-157
[Sequential Clarity: Navigation, Traceability].

In taxonomic reasoning tasks, such as scientific research or decision making, people gain insight and find new ideas through analysis of large numbers of factual data or material documents, which are generally disorganized and unstructured. Hypermedia technology provides effective means of organizing and browsing such information. However, for large amounts of information, the conventional node-link model makes linking or browsing operations complicated because relationships have to be represented as binary relations. In this paper, we propose a hypermedia data model called Frame-Axis Model, which represents relationship between information as N-ary relations on mapped space. Also, the automatic information organizing mechanism which is based on this data model and the browsing interface HyperCharts which employ spatial layout are provided. Finally, we show some browsing examples on our working prototype system, CastingNet.

Rasmussen, J. and K. J. Vicente (1989). "Coping with human errors through system design: Implications for ecological interface design." International Journal of Man Machine Studies **31**(5): 517-534
[Traceability].

Research during recent years has revealed that human errors are not stochastic events which can be removed through improved training programs or optimal interface design. Rather, errors tend to reflect either systematic interference between various models, rules, and schemata, or the effects of the adaptive mechanisms involved in learning. In terms of design implications, these findings suggest that reliable human-system interaction will be achieved by designing interfaces which tend to minimize the potential for control interference and support recovery from errors. In other words, the focus should be on control of the effects of errors rather than on the elimination of errors per se. In this paper, we propose a theoretical framework for interface design that attempts to satisfy these objectives. The goal of our framework, called ecological interface design, is to develop a meaningful representation of the process which is not just optimized for one particular level of cognitive control, but that supports all three levels simultaneously. The paper discusses the necessary requirements for a mapping between the process and the combined action/observation surface, and analyses of the resulting influence on both the interferences causing error and on the opportunity for error recovery left to the operator.

Tulving, E. and D. M. Thomson (1973). "Encoding specificity and retrieval processes in episodic memory." Psychological Review **80**: 352-373
[Cognition and Perception, Traceability].

Notes that recent changes in pretheoretical orientation toward problems of human memory have stimulated a concern with retrieval processes, resulting in a number of early versions of theories of retrieval. Explanations offered by these theories to account for the effect of extralist cuing (i.e., facilitation of recall of list items by nonlist items) are described and evaluated. In addition, 3 experiments with undergraduates (N = 76) tested the currently most popular theory of retrieval, the generation-recognition theory. Results were incompatible not only with generation-recognition models, but most other theories as well; under certain conditions Ss consistently failed to recognize many recallable list words. Several tentative explanations for this phenomenon of recognition failure were subsumed under the encoding specificity principle, according to which the memory trace of an event and hence the properties of effective retrieval cue are determined by the specific encoding operations performed by the system on the input stimuli. (91 ref) (PsycLIT Database Copyright 1974 American Psychological Assn, all rights reserved)

Yang, Y. (1988). A new conceptual model for interactive user recovery and command reuse facilities. Proceedings of ACM CHI'88 Conference on Human Factors in Computing Systems 165-170
[Traceability].

This paper generalises approaches to modeling an undo facility for interactive systems into a comprehensive user recovery and command reuse facility. It separates different undoing actions into distinct undoing functions and incorporates redoing capability in a more general command reuse capacity. Four adequacy criteria for such a facility are proposed and a general model is developed to meet these requirements. Partial, patterned and repetitive undoing and redoing actions are allowed on simple, complex and meta commands. The model subsumes the functionality of prior models.

Zapf, D., G. W. Maier, G. Rappensperger and C. Irmer (1994). "Error detection, task characteristics, and some consequences for software design." Applied Psychology An International Review **43**(4): 499-520
[Traceability].

Investigated the error detection (ED) of computer users in a field study and 2 laboratory experiments using word processing. There were 198 Ss (aged 16-60 yrs) from 11 German companies in the field study, 39 job training students in Exp 1, and 19 students in Exp 2. The ED rate of various types of errors, the impact of task complexity on error detection, and the question of computerized ED were examined. Results show a higher ED rate (96.5%) in the field study than in the experiments. Errors occurring in complex tasks were more difficult to detect. Moreover, 50% of all errors could be detected only by the users. Not more than 22% of the errors were detected with the help of the computer system. Errors in complex planning were the most difficult for computer supported ED. A strategy of error management is suggested that calls for the support of the process of error recovery through software design. (French abstract) (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

C. Context and Relations: Situate interactions within the broader context of the computer system and the user's experience.

C.1. Consistency: Make representations and functions common within and across tasks.

Aspillaga, M. (1991). "Screen design: Location of information and its effects on learning." Journal of Computer Based Instruction **18**(3): 89-92.
[Consistency].

Examined the effects of screen location of information displayed in computer-assisted instruction lessons on retention of the information. 60 undergraduates were assigned to 1 of 3 treatment conditions in which text was displayed (1) relevant to graphical information, (2) at the upper middle section of the screen, and (3) randomly. Results indicate that displaying information at a consistent location or relevant to graphical information facilitated learning. Location of information may serve as a mediator to recall by providing a natural picture that can be easily grasped, helping in organizing memory search. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved).

Kellogg, W. A. (1987). Conceptual consistency in the user interface: Effects on user performance. In Proceedings of IFIP INTERACT'87: Human Computer Interaction 389-394
[Consistency].

Consistency is often promoted as an important goal of user interface design, yet few definitions exist, particularly in a form suitable for guiding design. Most design guidelines stress procedural consistency, e.g., low-level interaction techniques, or the assignment of programmable function keys. This paper argues that interface consistency must also be addressed at a conceptual level. Conceptual consistency is defined in terms of the internal coherence of a system's structure and the nature of the mapping from user task goals to system procedures. Interfaces to an automated office system were constructed in which low-level interaction techniques were held constant, but which varied the degree of conceptual consistency. The results of a study in which users performed representative tasks on these systems is reported and discussed with respect to the importance of various kinds of consistency in the interface.

Lee, A. Y., P. W. Foltz and P. G. Polson (1994). "Memory for task-action mappings: Mnemonics, regularity, and consistency." International Journal of Human-Computer Studies **40**(5): 771-791
[Consistency].

Much of the knowledge required to use modern computing systems takes the form of mappings or associations. These occur between user goals and the functions that accomplish corresponding goals, between functions and the user actions that activate a desired function, and between a menu item or a button label and the function associated with that item or label. The question we explore in this paper is when is it worthwhile, if ever, for a user to pay the price of learning a set of new, regular task-action mappings that is inconsistent with the original set of task actions mappings of a previous version of a system. We consider three factors that determine the ease of learning and retention of task-action mappings: mnemonics, regularity within a set of mappings, and consistency of mapping across different system contexts. In two experiments, we found that Irregular-Non-Mnemonic mappings take much longer to master than

Regular-Mnemonic mappings and that Irregular-Non-Mnemonic mappings are more rapidly forgotten and subject to interference effects due to inconsistency. Regular-Non-Mnemonic mappings fall in-between the two groups: 1) they are easier to learn than Irregular-Non-Mnemonic mappings but harder than Regular-Mnemonic mappings, and 2) more items are retained for them than the Irregular-Non-Mnemonic mappings but fewer than for the Regular-Mnemonic mappings. We conclude that learning a new set Regular-Mnemonic task-action mappings is worthwhile even at the price of having to unlearn a well-learned set of old task-action mappings.

Lewis, C., D. C. Hair and V. Schoenberg (1989). Generalization, consistency, and control. In Proceedings of ACM CHI'89 Conference on Human Factors in Computing Systems, 1-5 [Consistency].

Easy learning of a user interface depends in part on users being able to generalize successfully about it. Philosophical doctrine, and some recent work in human-computer interaction, argues that causal analysis of interactions can support generalization. But neither the philosophical literature nor the HCI literature provides a rigorous theory of causal analysis adequate for problems in human-computer interaction. We propose such a rigorous theory here, and show how it accounts for two robust generalizations, using certain general assumptions. We then present evidence that these assumptions are accepted by people. Finally we compare this theory with other treatments of consistency.

Nielsen, J. (1989). Coordinating user interfaces for consistency. New York, Academic Press [Consistency].
Executive Summary:
Coordinating User Interfaces for consistency, Jakob Nielsen
The Dimensions of consistency , Wendy Kellogg
A Cost Benefit Analysis for Corporate User Interface Standards, Daniel J. Rosenberg
Coordinating consistency of User Interfaces, Code, Online Help, and Documentation with Multilingual/Multitarget Software Specification, Gary Perlman
Achieving consistency for the Macintosh, Bruce Tognazzini
Developing the XUI Style, Michael Good,The Lotus Experience, Richard Wolf
New Ways to Consistent Interfaces, Ianne Oritzinsky
Tools for Generating Consistent User Interfaces, Charlie Wiecha, William Bennett, Stephen Boies, and John Gould
Bibliography

Polson, P. G. (1988). The consequences of consistent and inconsistent interfaces. Hillsdale, NJ, Lawrence Erlbaum Associates, Inc.
[Consistency].

"[the book's] primary goal ...is to present a theoretical analysis and empirical findings on the effects of consistent user interfaces on learning and transfer of user skills. The cognitive complexity framework describes the theoretical basis of the analyses of consistency and inconsistency. The book summarizes three experiments demonstrating large positive transfer effects between various tasks within an application, between different versions of the same application, and between different applications."

Quinn, C. N. (1991). Explorability: inferences at the interface. Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences 570-576
[Consistency].

The problem of determining the appropriate action in using a new interface, or a new feature of a familiar interface, can be characterized as a form of problem-solving. Using distributed cognition as leverage to approach this problem, explorability is proposed as a framework within which to examine the inferences required to map the desired goal onto an appropriate action. Explorability is supported by consistency, affordances, and culture, each a constraint limiting the space of possible inferences. The three components are described, and the interaction of these three concepts is examined both as a problem and an opportunity for interface designers. The explorability framework is examined as an analytical tool to make explanations and predictions for interface designs.

Rieman, J., C. Lewis, R. M. Young and P. G. Polson (1994). "Why is a Raven like a writing desk?": Lessons in interface consistency and analogical reasoning from two cognitive architectures. Proceedings of the CHI '94 Conference on Human Factors in Computing Systems 438-444
[Consistency].

Users who have worked with just one or two pieces of application software on a computer system are often faced with the need to use a new piece of software on the same system. Consistency between program interfaces is intended to make the new program easier to learn in this situation, but how "consistency" should be defined is not always clear. We present a model of analogical reasoning that describes how users rely on interface consistency to induce correct actions in a new situation. Versions of the model are implemented in ACT-R and Soar. The model yields a clearer and more principled understanding of design guidelines that recommend interface consistency.

Tanaka, T., R. E. Eberts and G. Salvendy (1991). " Consistency of human-computer interface design: Quantification and validation." Human Factors **33**(6): 653-676.
[Consistency].

Attempted to integrate the research from human information processing with human-computer interaction applications by developing a model to quantify consistency for user interface designs and to test empirically the predictions from the model. The model called text-editing method was developed to quantify consistency between 2 tasks based on replacement, insertion, or deletion of methods. Two experiments involving a neural network simulation tested the predictions of the quantitative analyses of consistency for alternating tasks. Results confirm that similarities of 2 tasks and, thus, variability in the mapping of methods to overall task goals could have a detrimental effect on performance when the 2 tasks were performed in an alternating sequence. (PsycLIT Database Copyright 1992 American Psychological Assn, all rights reserved)

C.2. Familiarity: Use familiar terms, attributes, and relations among objects.

Joslyn, C., C. Lewis and B. Domik (1995). Designing Glyphs to Exploit Patterns in Multidimensional Datasets. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 198-199
[Familiarity].

Designing glyphs for revealing patterns in multidimensional data has been largely a trial-and-error process. We suggest that characteristics of human texture perception can provide useful guidance, allowing more effective glyphs to be designed. Using a combination of empirical study of existing glyphs and analysis of the Bergen and Landy [1] model of texture perception, we developed improved versions of existing glyphs and a new glyph, all effective in revealing certain simple regularities in data.

Kamada, T. and S. Kawai (1991). "A General Framework for Visualizing Abstract Objects and Relations." ACM Transactions on Graphics **10**(1): 1-39
[Familiarity, Evaluation].

Pictorial representations significantly enhance our ability to understand complicated relations and structures, which means that information systems strongly require user interfaces that support the visualization of many kinds of information with a wide variety of graphical forms. At present, however, these difficult visualization problems have not been solved. We present a visualization framework for translating abstract objects and relations, typically represented in textual forms, into pictorial representations, and describe a general visualization interface based on this framework. In our framework, abstract objects and relations are mapped to graphical objects and relations by user-defined mapping rules. The kernel of our visualization process is to determine a layout of graphical objects under geometric constraints. A constraint-based object layout system named COOL has been developed to handle this layout problem. COOL introduces the concept of rigidity of constraints in order to reasonably handle a set of conflicting constraints by use of the least squares method. As applications of our system, we show the generation of kinship diagrams, list diagrams, Nassi-Shneiderman diagrams, and entity-relationship diagrams.

Robertson, G. G. and J. D. Mackinlay (1993). The Document Lens. Proceedings of the ACM SIGGRAPH Symposium on User Interface Software and Technology 101-108
[Familiarity, Example].

This paper describes a general visualization technique based on a common strategy for understanding paper documents when their structure is not known, which is to lay the pages of a document in a rectangular array on a large table where the overall structure and distinguishing features can be seen. Given such a presentation, the user wants to quickly view parts of the presentation in detail while remaining in context. A fisheye view or a magnifying lens might be used for this, but they fail to adequately show the global context. The Document Lens is a 3D visualization for large rectangular presentations that allows the user to quickly focus on a part of a presentation while continuously remaining in context. The user grabs a rectangular lens and pulls it around to focus on the desired area at the desired magnification. The presentation outside the lens is stretched to provide a continuous display of the global context. This stretching is efficiently implemented with affine transformations, allowing text documents to be viewed as a whole with an interactive visualization.

Stone, M. C., K. Fishkin and E. A. Bier (1994). The Movable Filter as a User Interface Tool. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 221 [Familiarity].

Magic Lens filters are a new user interface tool that combine an arbitrarily-shaped region with an operator that changes the view of objects viewed through that region. These tools can be interactively positioned over on-screen applications much as a magnifying glass is moved over a newspaper. This paper describes their advantages in more detail and illustrates them with examples of magic lens filters in use over a variety of applications.

Willie, S. (1994). Query Context: Would a Graphical Interface Help? Proceedings of OZCHI'94, the CHISIG Annual Conference on Human-Computer Interaction 141-146 [Familiarity, Expertise].

The paradox of electronic storage of information is that it can make information unavailable to the general public. The known problems with Boolean query constructs in conjunction with the complexities of computer access and even an inappropriate mental model of the information space overwhelm the general user. While the graphical user interface has been shown to decrease memory load, it does not provide support for direct manipulation in information search. This paper looks at our current research into a graphical query interface which we believe has the potential to ameliorate the current situation and lead to easier access to electronic information spaces for novice and infrequent users.

C.3. Situation: Make clear the context in which an object or action occurs and the constraints on its use.

Bearne, M., S. Jones and J. Sapsford-Francis (1994). Towards usability guidelines for multimedia system. Proceedings of ACM Multimedia '94 105-110
[Situation].

The advent of technology which supports the concurrent presentation of information through a range of different media has raised new issues relating to the design of usable systems. While previous work in the areas of both Human-Computer Interaction (HCI) and hypermedia system usability can contribute a considerable amount to the development of such guidelines, we believe that the use of multiple output media demands an understanding of particular characteristics and limitations of users' attentional capabilities. This paper presents some initial guidelines for the design of usable multimedia systems. These guidelines are based on empirical findings regarding the nature of human attention derived from the field of experimental psychology. We believe that the provision of such guidelines for multimedia interface design will support designers in achieving the dual goals of, maximizing a user's flexibility in controlling the presentation of multiple concurrent media, while keeping cognitive load to an acceptable level. (21 Refs.)

Ingwersen, P. (1994). Polyrepresentation of Information Needs and Semantic Entities: Elements of a Cognitive Theory for Information Retrieval Interaction. Proceedings of the Seventeenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 101-110
[Situation, Preference].

The paper outlines the principles underlying the theory of polyrepresentation applied to the user's cognitive space and the information space of IR systems, set in a cognitive framework. By means of polyrepresentation it is suggested to represent the current user's information need, problem state, and domain work task or interest in a structure of causality as well as to embody semantic full-text entities by means of the principle of 'intentional redundancy'. In IR systems this principle implies simultaneously to apply different methods of representation and a variety of IR techniques of different cognitive origin to each entity. The objective is to approximate as close as possible text retrieval to retrieval of information in a cognitive sense.

McAleese, R. (1987). The graphical representation of knowledge as an interface to knowledge based systems. Proceedings of IFIP INTERACT'87: Human Computer Interaction 1089-1093
[Situation].

This paper reports on a technique for portraying the detail and the extent of knowledge on a graphical interface. Research has centered on concept maps which derive from ideas such as "hypertext". Such maps represent the structure and inter-connections between concept labels in knowledge structures. A "map" is a bounded view of one aspect of the overall knowledge-data structure. A map is a synonym for a browser. Users can decompress (expand) or compress (reduce to a minimal level) concept relationships based on selection criteria. This map metaphor is based on cognitive theory that supports the representation of knowledge. In knowledge elicitation the chosen interface gives the expert a network metaphor of their knowledge. Each concept (concept label) can be seen as a label with a finite set of links. As the knowledge structure grows a variety of browsers allow the user to see all or part of the knowledge base. Users can select a topic label as the starting point for a browser, define its limits and specify the type of links (relationships) to be included. Such an interface is a powerful tool as it uses the human eye, which has under used channel capacity, to process complex data structures. The system has been implemented on a workstation which allows multiple windows in a WIMP environment. Knowledge can be entered at any level, compressed (top to down) or decompressed (bottom to up). The system (called KIM: Knowledge and Information Mapping) keeps integrity between different views. The paper reports on user trials with the system. It suggests that problems can arise when the user can not easily reconcile different views and perspectives. The paper highlights the importance of "terrain knowledge" of knowledge based systems (global views), in addition to "street knowledge" (local views).

Strong, G. W. and K. O. Strong (1991). “Visual guidance for information navigation: A computer-human interface design principle derived from cognitive neuroscience.” Interacting with Computers **3**(2): 217-231
[Situation].

Interprets for computer-human interface (CHI) designers the separation between "what" and "where" information-processing pathways in the human brain. This interpretation is applied to the derivation of a principle for CHI design that helps solve the problem of navigating information spaces, using the HyperCard application as an example. The principle of natural affordances says that a computer screen display should clearly indicate the possible behaviors/responses available and that the user should be able to learn conceptual models via the behavioral responses that are afforded on the individual screens. (PsycLIT Database Copyright 1993 American Psychological Assn, all rights reserved)

D. Adaptability: Make the system responsive to ranges of tasks and user abilities.

D.1. Expertise and Training: Make the system interaction capable of varying with the degree of user expertise.

Caird, J. K. and P. A. Hancock (1991). Perceived Spatial Layout of a Simulated Scene as a Function of Experience. Proceedings of the Human Factors Society 35th Annual Meeting 1447-1451
[Structural Integrity: Depth Cues, Expertise].

A critical question in simulation is the degree of correspondence or alignment between what is seen in a generated graphics world and it's intended actual physical structure. An allied concern, is the role of perceptual experience as a potential influence on this perceived spatial layout. The present experiment examined the potential for these perceived distortions. Eight observers estimated the location of nine object locations embedded in a graphical scene of a traffic intersection. Participants were asked to judge the relative and absolute distances between objects in the display. Half the subjects viewed the intersection after driving for thirty minutes through the simulated traffic world while the remaining participants did not receive any prior experience. A multidimensional scaling analysis revealed differences between simulator and no simulator experience groups for absolute and relative 3-D solutions. Scaled representations of actual and perceived spaces are discussed in the framework of a model of perceived spatial layout and with respect to human factors issues in the use of both simulated and virtual worlds.

Juhel, J. (1991). “Spatial abilities and individual differences in visual information processing.” Intelligence **15**(1): 117-137
[Expertise].

Explored individual differences in performance in visual memory and recognition tasks as a function of performance in spatial tests with 90 college students (aged 18-35 yrs) who underwent a battery of spatial tests and laboratory tasks. Factor analysis supports (1) the validity of the distinction between a spatial visualization factor and a speeded rotation factor and (2) the assumption of a relatively low overlap between spatial tests and cognitive tasks. When different groups of Ss were contrasted according to visual memory and spatial visualization dimensions, study of mean latencies of these groups in visual-spatial computerized tasks established that efficiency of encoding and information organization processes were reflected by the visual memory dimension. The spatial visualization dimension corresponded with the quality of information transformation processes as well as with strategic selections.

Osborn, J. R. and A. M. Agogino (1992). An Interface for Interactive Spatial Reasoning and Visualization. Proceedings of ACM CHI'92 Conference on Human Factors in Computing Systems 75-82
[Expertise, Diversity].

An interface for software that creates a natural environment for engineering graphics students to improve their spatial reasoning and 3D visualization skills is described. The skills of interest involve spatial transformations and rotations, specifically those skills that engineers use to reason about 3D objects based on 2D representations. The software uses an intuitive and interactive interface allowing direct manipulation of objects. Animation capability is provided to demonstrate the relationship between arbitrary positions of an object and standard orthographic views. A second skill of interest requires visualization of a cutting-plane intersection of an object. An interface is developed which allows intuitive positioning of the cutting-plane utilizing the metaphor of a "pool of water" in which the object is partially submerged. The surface of the water represents the cutting plane. Adjustment of the pool depth combined with direct manipulation of the object provides for arbitrary positioning of the cutting-plane. Subjective evaluation of the software thus far indicates that students enjoy using it and find it helpful. A formal testing plan to objectively evaluate the software and interface design is underway.

Vicente, K. J., K. Christoffersen and A. Pereklita (1995). “Supporting operator problem solving through ecological interface design.” IEEE Transactions on Systems, Man, and Cybernetics **25**(4): 529-545
[Expertise].

Conducted 2 experiments using 36 adults of varying expertise to evaluate ecological interface design (EID) for complex human-machine systems. Two interfaces for a thermal-hydraulic process simulation were developed, one containing only physical information (P) and another which also contained information about higher-order functional variables (P+F). Findings of Exp 1 support the claim that an interface based on an abstraction hierarchy representation can provide more support for problem solving than an interface based on physical variables alone. There was also some evidence that theoretical expertise is required to enjoy the full benefits of the P+F interface. Findings of Exp 2 indicate that Ss who exhibited effective diagnosis performance using the P+F interface tended to start their search at a high level of abstraction and gradually work their way down to more detailed levels, as predicted. (PsycLIT Database Copyright 1995 American Psychological Assn, all rights reserved)

D.2. Diversity: Take into account differences in perceptual, cognitive, and motor characteristics of the user population.

Allen, B. (1994). Perceptual Speed, Learning and Information Retrieval Performance. Proceedings of the Seventeenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 71-80
[Diversity].

Although the cognitive ability "perceptual speed" is known to influence search performance by end-users, previous research has not established the mechanism by which this influence occurred. Results from educational psychology suggest that learning that occurs during searching is likely to be influenced by perceptual speed. An experiment was designed to test how this cognitive ability would interact with a system feature designed to enhance learning of search vocabulary, specifically, presenting subject descriptors as the first element in the display of a reference. Results showed significant interactions between perceptual speed and the order of presentation of data elements in predicting both vocabulary learning and search performance. Those results indicate that searchers with higher levels of perceptual speed will learn additional search vocabulary, and use that vocabulary to complete higher quality searches, when they use a system designed to optimize scanning of subject descriptors. This outcome supports the idea that cognitive abilities influence information system usability, and that usability is determined by interactions between characteristics of users and system features. The findings also suggest that system features that enhance the learning of search vocabulary, such as query expansion mechanisms, can have a significant positive effect on the quality of end-user searching.

Chen, C. and R. Rada (1996). “Interacting with hypertext: A meta-analysis of experimental studies.” Human Computer Interaction **11**(2): 125-156
[Diversity].

Conducted a meta-analysis to compare the results of 23 experimental studies on hypertext. The analysis was based on 56 pairs of effect sizes and significance levels of the impact of users, tasks, and tools on interactions with hypertext. This analysis focused on 3 factors that influence the use of hypertext: the cognitive styles and spatial ability of users, the complexity of tasks, and the structure of information organization and the visualization of the structure. These studies reported significantly discrepant findings, indicating that substantial differences exist among individual experiments. Individual differences in cognition did not yield enough evidence to conclude that the effect sizes are significantly apart from zero. The meta-analysis showed that the overall performance of hypertext users tended to be more effective than that of nonhypertext users, but the differences in efficiency measures were consistently in favor of nonhypertext users.

Hegarty, M. and V. K. Sims (1994). “Individual differences in mental animation during mechanical reasoning.” Memory and Cognition **22**(4): 411-430
[Structural Integrity, Diversity].

Three experiments tested the effects of spatial visualization ability on performance of a motion-verification task in which Ss (102 undergraduates) were shown a diagram of a mechanical system and were asked to verify a sentence stating the motion of one of the system components. Compared with Ss with high spatial ability, Ss with low spatial ability made more errors overall and made more errors on items in which more system components had to be animated to solve the problem. Ss with high spatial ability were relatively accurate on all trials. Reaction time (RT) and eye-fixation data reveal no differences in how high- and low-spatial Ss decomposed the task. Data of the 2 types of Ss are equally consistent with a piecemeal model of mental animation in which components are animated one by one in order of the causal chain of events in the system.

Juhel, J. (1990). "Differences individuelles dans le traitement de l'information spatiale. (Individual differences in the processing of spatial information.)." Revue de Psychologie Appliquee **40**(3): 331-356
[Diversity].

Reviews research on individual differences in spatial ability, with a focus on studies based on the information processing approach. Two research directions are emphasized: (1) psychometric studies of performance on spatial tasks, and (2) cognitive analyses of performance on spatial tasks. Research on the factorial structure of spatial ability has identified 3 main factors of spatial ability: spatial orientation, spatial visualization, and speed of mental rotation. Cognitive research indicates that individual differences in spatial information processing lie in the quality of mental representations, the efficiency of transformation processes, and processing strategies. (English abstract)

Mislevy, R. J., M. S. Wingersky, S. H. Irvine and P. L. Dann (1991). "Resolving mixtures of strategies in spatial visualization tasks." British Journal of Mathematical and Statistical Psychology **44**(2): 265-288
[Diversity].

Examines knowledge structures and problem-solving strategies by describing key qualitative distinctions among persons as to structures and strategies through mixtures of test theory models and draws on substantive theory to delineate the components of the mixture. This approach is illustrated with data from 196 naval engineering cadets who performed spatial visualization tasks that can be solved by mental rotation or by a nonrotational rule-based strategy. It is assumed that an S employs the same strategy on all tasks, but the possibility of extending the approach to strategy-switching is discussed.

Salthouse, T. A., R. L. Babcock, D. R. Mitchell, R. Palmon and et al. (1990). "Sources of individual differences in spatial visualization ability." Intelligence **14**(2): 187-230
[Diversity].

Conducted 2 experiments testing 3 hypotheses on individual differences in spatial visualization ability (SVA), concerning (1) representational quality, (2) transformational efficiency, and (3) preservation of representations during transformations. SVA differences for a total of 142 male undergraduates (17-30 yrs) were assessed using 4 paper-and-pencil tests. Findings fail to support the 1st 2 hypotheses but provide some support for the 3rd. SVA differences were most pronounced when some information had to be preserved while the same or other information was being processed. D. E. Broadbent's (1971) desktop analogy of working memory is used to explain the results.

Seagull, F. J. and N. Walker (1992). "The effects of hierarchical structure and visualization ability on computerized information retrieval." International Journal of Human Computer Interaction **4**(4): 369-385

[Diversity].

Examined the effects of visualization ability on search time in databases with different hierarchical structures to determine whether manipulation of the hierarchical structures of information could accommodate the needs of low-visualization ability users. The task consisted of finding specific "target" files in each of the 4 different data structures that varied in depth of organization. Results from 44 undergraduates suggest that individual differences in performance are the result of differences in perceptual speed and that altering the structure of the information in a database is not an effective way to accommodate low-visualization ability users.

Sein, M. K., L. Olfman, R. P. Bostrom and S. A. Davis (1993). "Visualization Ability as a Predictor of User Learning Success." International Journal of Man-Machine Studies **39**(4): 599-620
[Diversity].

A novice user's cognitive abilities can influence how difficult he/she finds learning to use a software package. To ensure effective use, it is important to identify specific abilities that can influence learning and use, and then develop training methods or design interfaces to accommodate individuals who are lower in those abilities. This paper reports the integrated findings of five studies that examined a specific cognitive variable, visualization ability, for different systems (electronic mail, modeling software and operating systems), applying different training methods (analogical or abstract conceptual models) and computer interfaces (command-based or direct manipulation). Consistent with past results in other domains, we found that visualization ability is a strong predictor of user learning success. More importantly, we also found that subjects with lower visualization ability can be helped to narrow, and in some cases equal or surpass, the performance gap between themselves and subjects with higher visualization ability through appropriate training methods and direct manipulation interfaces. Based on our findings, we discuss implications for practitioners and designers and suggest possible avenues for future research.

Seron, X., M. Pesenti, M. P. Noel, G. Deloche and et al. (1992). "Images of numbers: or "When 98 is upper left and 6 sky blue." Special Issue: Numerical cognition." Cognition **44**(1-2): 159-196
[Diversity].

Some people declare that they possess a personal visual representation of numbers: Some automatically "see" the numbers they are confronted with in a precise location in a structured mental space, and others "associate" specific colors with given numbers. Such visuospatial representations of numbers (number-forms) were first described by F. Galton in 1880 but have since received little attention from psychologists. The authors describe these mental representations and discuss their role in number processing. Exploratory data are presented from controlled experiments with 2 cases: a 23-yr-old female claiming to have a colored code for digits and a 17-yr-old male claiming to possess a scale number-form. The relevance of these visuospatial representations to contemporary debates on number representation and calculation is discussed.

Stanney, K. M. and G. Salvendy (1995). "Information visualization; assisting low spatial individuals with information access tasks through the use of visual mediators." Ergonomics **38**(6): 1184-1198
[Diversity].

Compared the use of a 2-dimensional hierarchical visual mediator (VM) with that of a linear structure as a VM for accommodating low spatial Ss. In Part 1, 74 college students were administered cognitive tests and an S-data questionnaire. In Part 2, 24 of the Ss (12 high spatial and 12 low spatial) performed an information search task on 3 interface designs (challenge, hierarchical, and linear). The dependent variables were performance time, general satisfaction, task-specific satisfaction, mental workload, and overall workload, while the independent variables were S group, interface design, and sequence. By providing VMs that removed the need to construct a mental model of embedded information, both of the compensatory match interfaces (hierarchical and linear) were successful at accommodating low spatial Ss.

West, T. G. (1992). "A future of reversals: Dyslexic talents in a world of computer visualization." Annals of Dyslexia **42**: 124-139
[Diversity].

Proposes that visually oriented dyslexics may be in an increasingly favorable position in future years because of the recent revival of visual approaches to scientific, mathematical, and technological developments. The same set of traits that has caused them so much difficulty in traditional verbally oriented educational systems may provide special advantages in emerging new fields that rely on visual methods of analysis: fields that use graphic workstations and supercomputers to visualize complex scientific data. Recent trends have led technical professionals to become aware that their own special talents seem to be associated with dyslexic traits. Similar mixed talents have been major factors in the accomplishments of a number of historical figures (i.e., Albert Einstein, Leonardo da Vinci).

D.3. Preference, Control, and Collaboration: Enable the interface to adapt based on usage patterns, the user's desired level of control, and interaction with other users.

Deck, J. G. and M. M. Sebrechts (1984). "Variations on active learning." Behavior, Research Methods, Instruments, and Computers **16**: Behavior, Research Methods, Instruments, and Computers
[Preference, Diversity].

Four experienced computer users were asked to learn a system that they had not previously used. A few weeks after training they were asked to provide a description of the system in words and diagrams. Analysis of the verbal protocols suggested that active learning varied on at least 2 dimensions: schema orientation and learning strategy. Some Ss preferred to be internally driven and form their own plans for learning and others were externally driven and allowed the instructional materials to guide their learning. These differences need to be taken into account in describing learning and in designing instructional materials. (18 ref) (PsycLIT Database Copyright 1985 American Psychological Assn, all rights reserved)

Fischer, G. and A. Girgensohn (1990). End-user modifiability in design environments. Proceedings of the CHI '90 Conference on Human Factors in Computing Systems 183-192
[Preference].

Convivial systems encourage users to be actively engaged in generating creative extensions to the artifacts given to them. Convivial systems have the potential to break down the counterproductive barrier between programming and using programs. Knowledge-based design environments are prototypes for convivial systems. These environments support human problem-domain communication, letting users work within their domains of expertise. One of the design rationales behind design environments is to ease the construction and modification of artifacts designed within the environment. But because design environments are intentionally not general purpose programming environments, situations will arise that require modifications to the design environment itself. The rationale and the techniques for these later modifications are discussed in this paper. Our conceptual framework for end-user modifiability is illustrated in the context JANUS, an environment for architectural design. Evaluating our system building efforts against our objectives shows the subtleties of integrating end-user modifiability in these kinds of systems.

Hollan, J. D. (1990). User models and user interfaces: a case for domain models, task models, and tailorability. In Proceedings of AAAI-90, Eighth National Conference on Artificial Intelligence,
[Preference].

The case for user models has little empirical support, necessarily must confront currently intractable problems, and is motivated by aspects of a metaphor that presently, are not an effective base for the design of user interfaces. Some of what is sought in the name of user modeling can be accomplished by basing interface design on models of application domains, user tasks, and by providing tailorable systems. (2 Refs.)

Macaulay, L. A. and M. A. Norman (1984). Designing interfaces for different types of users - experimental criteria. In Proceedings of IFIP INTERACT'84: Human Computer Interaction 643-647
[Preference].

The nature of the user interface should be adaptive to accommodate variations in user skill levels and cognitive style. The paper includes a brief review of current research on dialogue design, and describes aspects of an experiment carried out into the use of functional simplicity in dialogue design. The experimental session is described briefly and results based on keystroke timings are reported upon. Further findings from the experiments are reported upon elsewhere, including [16].

Mackay, W. E. (1991). Triggers and barriers to customizing software. Proceedings of ACM CHI'91 Conference on Human Factors in Computing Systems 153-160
[Preference].

One of the properties of a user interface is that it both guides and constrains the patterns of interaction between the user and the software application. Application software is increasingly designed to be "customizable" by the end user, providing specific mechanisms by which users may specify individual preferences about the software and how they will interact with it over multiple sessions. Users may thus encode and preserve their preferred patterns of use. These customizations, together with choices about which applications to use, make up the unique "software environment" for each individual. Although it is easier than it previously ever has been to specify preferences and optimize each possible customization option, this study suggests that most people do not. In fact, since time spent customizing is time spent not working, many people do not take advantage of the customization features at all. I studied the customization behavior of 51 users of a Unix software environment, over a period of four months. This paper describes the process by which users decide to customize and examines the factors that influence when and how users make those decisions. These findings have implications for both the design of software and the integration of new software into an organization.

Malone, T. W. (1983). How do people organize their desks? Implications for the design of office information systems. ACM Transactions on Office Information Systems 99-112
[Preference].

This paper describes a series of interviews focusing on the way professional and clerical office workers organize the information in their desks and offices. A number of implications for designing "natural" and convenient computer-based information systems are discussed. organization is to remind the user of things to do, not just to help the user find desired information. Failing to support this function may seriously impair the usefulness of electronic office systems, and explicitly facilitating it may provide an important advantage for automated office systems over their nonautomated predecessors. (2) The cognitive difficulty of categorizing information is an important factor in explaining how people organize their desks. Computer-based systems may help with this difficulty by (a) doing as much automatic classification as possible (e.g., based on access dates), and (b) including untitled "piles" of information arranged by physical location as well as explicitly titled and logically arranged "files." Several other implications for the design of electronic office systems are discussed, and some differences in how people organize their desks are described.

Olson, J. R., S. K. Card, T. K. Landauer, G. M. Olson and e. al. (1993). “Computer-supported co-operative work: Research issues for the 90s.” Behaviour and Information Technology **12**(2): 115-129
[Preference].

Reviews the current state of the art of computer-supported cooperative work (CSCW), which refers to group work that can be supported by some kind of technology. There is a need for theories and models, for guidelines on interaction styles, and for toolkits and user interface management systems. Two research areas involve the physical setting of CSCW and a better characterization of this type of work. Current trends in CSCW include research on group support systems, electronic mail, and group authoring systems. (PsycLIT Database Copyright 1993 American Psychological Assn, all rights reserved)

Totterdell, P. A., M. A. Norman and D. P. Browne (1987). Levels of adaptivity in interface design. Proceedings of IFIP INTERACT'87: Human Computer Interaction 715-722.
[Preference].

The term adaptation has been used variously to describe computer systems which are personalisable by either designer or user, systems which fixedly change in response to user or application features and to systems which assess the value of their changes. This paper attempts to identify a coherent framework into which these seemingly disparate systems can be mapped. The foundation for the framework originates from the observation that adaptation relates a system to its environment. A number of levels of adaptivity are revealed by using a model of the computational strategies which can be applied in playing game theory's prisoners dilemma. Sufficiency and boundedness are introduced as key concepts. The levels are reinterpreted by looking at an account of adaptation in evolution. The adaptivity argument is then discussed in the context of explanation types in science and in particular Bechtel's realistic-intentional approach. Some design methodology principles for adaptive systems are suggested with Dennett's notional worlds as a first step in the design. Finally, the paper identifies a taxonomy for adaptive systems and reviews the state of the art in computer adaptive systems with respect to the taxonomy.

Tyler, S. W. (1988 .). SAUCI: A knowledge-based interface architecture. Proceedings of ACM CHI'88 Conference on Human Factors in Computing Systems 235-240
[Preference].

Most current approaches to the design of the human-computer interface result in systems that are difficult for users to master. This can be attributed to the absence of several key features, including: interface modularity; adaptability to the individual user; direct support of user intentions; and an intelligent advising capability. An architecture for the interface which facilitates the attainment of these four criteria is proposed. The architecture relies upon production system rules and various kinds of knowledge bases to tailor the user-computer dialogue to the ongoing context of the interaction. A prototype of this architecture has been implemented in LOOPS for interfacing to the UNIX system, and has been shown to enhance substantially the performance of novice users of the system.

Tyler, S. W. and S. Treu (1989). “An interface architecture to provide adaptive task-specific context for the user.” International Journal of Man Machine Studies **30**(3): 303-327

[Preference].

An abstract architecture for the design of user-computer interfaces is described. It is intended to serve the user-oriented principles of learnability and usability. The primary interface features selected as responsive to these principles are task-specific context presented to the user, reinforced by system adaptability to users needs. Both of these features are undergirded by interface system modularity. Context is defined to include not only high-level direction and step-by-step guidance toward task completion but also intelligent advice on the different user actions and commands. A prototype interface system was implemented, using a Xerox 1108 LISP workstation and a VAX 11/780 UNIX system as the target computer. It was organized around the definition of a multi-phase interaction event flowchart and is very dependent on object-oriented and rule-based paradigms. Limited test results indicate a favorable performance pattern.

IV. Interface Evaluation

Boyd, C. (1995). Human and Machine Dimensions of 3D Interfaces for Virtual Environments. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 41-42
[Input Compatibility: Navigation, Evaluation,].

This work explores two categories for evaluating and measuring virtual environment (VE) interfaces. One category concerns characteristics of the interface, such as its complexity and abstractness. The other category concerns the human capacities for understanding and using three-dimensional input/output devices. The results may help us predict the usability of VE interfaces and help us to design interfaces that are well matched to their intended users.

Carswell, C. M. (1992). "Choosing specifiers: An evaluation of the basic tasks model of graphical perception. Special Issue: Visual displays." Human Factors **34**(5): 535-554
[Interface Design, Evaluation].

Used effect sizes from 39 experiments to evaluate the predictions of the basic tasks model of graphical efficacy. This model predicts that performance will be attenuated with graphical displays as a function of the particular specifier used to code data values. In this review the basic tasks model predicted performance more accurately than did E. R. Tufte's (1983, 1990) data-ink principle. In addition, variability in effect size across studies revealed that the model was more successful at predicting performance in local tasks than in global information synthesis tasks, as well as in tasks requiring the use of physically present rather than remembered graphs. Minimal differences were obtained among graphs that used position, length, or angle as specifiers. However, graphs that used area or volume to represent quantitative values were associated with consistently worse performance than found with other formats. (PsycLIT Database Copyright 1993 American Psychological Assn, all rights reserved)

Cuomo, D. L. and C. D. Bowen (1994). "Understanding usability issues addressed by three user-system interface evaluation techniques." Interacting with Computers **6**(1): 86-108
[Evaluation].

Three evaluation techniques (cognitive walk-through, heuristic evaluation, and the S. L. Smith and J. N. Mosier (1986) guidelines) were applied to a graphical, direct-manipulation (DM) style of interface for a prototyped airspace scheduling system. The authors determined whether the techniques identified problems (1) that occur across all stages of the user activity model, (2) that are specific to the usability of graphical DM-style systems, and (3) that noticeably affect users' performance with the system. A usability study was conducted with 5 human factors professionals. Problems predicted by the structured judgment techniques were compared to the test results to determine which of the predicted usability problems affected user performance. Of the 3 methods, the guidelines appear more likely to find problems for each stage, with heuristic evaluation next. Cognitive walk-through did very well in the action specification stage. (PsycLIT Database Copyright 1994 American Psychological Assn, all rights reserved)

Dumais, S., N. Belkin, C. L. Borgman and M. Hancock-Beaulieu (1994). Evaluating Interactive Retrieval Systems. Proceedings of the Seventeenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 361
[Evaluation].

Most current information retrieval systems are highly interactive. Users ask queries, get immediate feedback, refine their queries, and so on. Methods for evaluating these dynamic systems have not kept pace with the rapid advances in system design. It is no longer enough to use the standard precision-recall measures to evaluate and to improve interactive retrieval systems. There is often no single final query to evaluate, with useful information being gathered from many different queries along the way. In addition, interfaces play a critical role in building effective retrieval systems. The best retrieval algorithm can be rendered functionally useless if the interface to it is unusable. Conversely, of course, the spiffiest new interface is not worth much without a good retrieval engine behind it. It would be easy if one could study interfaces and retrieval engines separately and take the best of both worlds. Unfortunately, there are important interactions that cannot be evaluated by studying components in isolation -- e.g., how do you incorporate ranking or relevance feedback for a Boolean retrieval engine, or how do you highlight matching terms if complex syntactic and semantic processing of queries is used? The design of effective interactive retrieval environments will require careful attention to the larger human - interface - retrieval-engine system. are possible both in the laboratory and in the field. The panelists described interactive retrieval experiments and experiences, focusing on: a) why it is important to study interactions b) how interactive retrieval performance should be measured, and c) how the methods for evaluation and findings generalize to other systems. Belkin begin with an overview of some of the problems in evaluating interactive retrieval systems and presented a new framework characterizing IR as interaction with text. The remaining talks described end-user experiments involving highly interactive retrieval systems. The focus of these talks were on the approaches, methods and instruments used to evaluate retrieval effectiveness and ease of use as well as the relationship between system functionality and the interface. Dumais described the importance of interfaces in retrieval, and presented examples of successful iterative interface design with the SuperBook and X-LSI systems. Hancock-Beaulieu reviewed a series of experiments on the Okapi system to systematically examine the effectiveness of different retrieval aids. Bergman described the multiple evaluation methods employed to study children's information-seeking behavior using the Science Library Catalog, a graphical browsing system supplemented by keyword searching tailored to children's skills, and attempted to generalize these evaluation methods to other IR environments.

Gallimore, J. J. and M. E. Brown (1993). "Visualization of 3-D Computer-Aided Design Objects." International Journal of Human-Computer Interaction 5(4): 361-382
[Structural Integrity: Depth Cues, Input Compatibility, Evaluation].

There are many significant human factors issues associated with the design and visualization of complex, computer-generated images. One such issue is to determine the most effective techniques for providing engineers with realistic three-dimensional (3-D) objects. Differences in subjects' ability to discriminate between the shape of two 3-D, perspective, computer-aided design-type (CAD-type) objects were investigated for various levels of monocular coding techniques and the binocular cue stereopsis. Performance was assessed at all combinations of five levels of monocular cues and two levels of disparity. The task was similar to the classic mental rotation paradigm except that subjects were provided with the ability to rotate one of the objects using a two-dimensional (2-D) joystick. Results indicate that interposition was the only depth cue that significantly enhanced subject performance. One explanation for the lack of significance of stereopsis is that, for this particular task, depth information provided by disparity was not needed. Detailed analysis of object rotation data using an orientation index (OI) suggests that subjects employed a feature-by-feature comparison task strategy. With tools that can evaluate cognitive activity such as the mental rotation paradigm and orientation index, researchers can learn more about how designers visualize and understand 3-D CAD objects.

Grissom, S. B. and G. Perlman (1995). "StEP(3D): A Standardized Evaluation Plan for Three-Dimensional Interaction Techniques." International Journal of Human-Computer Studies **43**(1): 15-41
[Evaluation].

Usability evaluation is a critical component of software development. However skills necessary to develop a valid and reliable evaluation plan may deter some organizations from performing usability evaluations. These organizations would benefit by having an evaluation plan available to them that was already designed for their needs. A standardized evaluation plan (StEP) is designed to evaluate or compare a wide variety of systems that share certain capabilities. StEPs are developed for a specific domain by usability specialists. These plans can then be used by evaluators with limited experience or facilities because the skills necessary to use a StEP are not as demanding as the skills needed to develop a StEP. flexible and responsive to the user but the usability of these techniques have generally not been evaluated empirically. StEP(3D), a standardized evaluation plan for the usability of three-dimensional interaction techniques, combines performance-based evaluation with a user satisfaction questionnaire. It is designed to be portable and simple enough that evaluators can make comparisons of three-dimensional interaction techniques without special equipment or experience. It evaluates the usability of interaction techniques for performing quick and unconstrained three-dimensional manipulations. Two empirical experiments are reported that demonstrate the reliability and validity of StEP(3D). Experiment 1 shows StEP(3D) is appropriate for comparing techniques on different hardware platforms during summative evaluations. Experiment 2 shows StEP(3D) is sensitive enough to detect subtle changes in an interface during formative design. on our experiences with the development of StEP(3D). However, the recommendations are not limited to three-dimensional interaction techniques. Most of the recommendations apply to the development of StEPs in any domain and address issues such as portability, participant selection, experiment protocol and procedures, and usability measures. A collection of StEPs designed for particular domains and purposes would provide a library of reusable evaluation plans. This reusable approach to usability evaluation should reduce the cost of evaluations because organizations are able to take advantage of previously designed plans. At the same time, this approach should improve the quality of usability evaluations because StEPs are developed and validated by usability specialists.

Hinckley, K., R. Pausch, J. C. Goble and N. F. Kassell (1994). A Survey of Design Issues in Spatial Input. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 213-222
[Input Compatibility, Evaluation].

A survey of design issues for developing effective free-space three-dimensional (3D) user interfaces. The survey is based upon previous work in 3D interaction, our experience in developing the free-space interfaces, and our informal observations of test users. We illustrate our design issues using examples drawn from instances of 3D interfaces. For example, our first issue suggests that users have difficulty understanding three-dimensional space. We offer a set of strategies which may help users to better perceive a 3D virtual environment, including the use of spatial references, relative gesture, two-handed interaction, multisensory feedback, physical constraints, and head tracking. We describe interfaces which employ these strategies. Our major contribution is the synthesis of many scattered results, observations, and examples into a common framework. This framework should serve as a guide to researchers or systems builders who may not be familiar with design issues in spatial input. Where appropriate, we also try to identify areas in free-space 3D interaction which we see as likely candidates for additional research. An extended and annotated version of the references list for this paper is available on-line through mosaic at address http://uvacs.cs.virginia.edu/~kph2q/.

Jones, R. W. and I. E. Careras (1996). "The empirical investigation of factors affecting graphical visualization." Behavior Research Methods, Instruments and Computers **28**(2): 265-269
[Evaluation].

Describes Graphics Visualization (GV), a computer software tool which offers an inexpensive, accurate, and reliable method of performing empirical research on the factors that affect the accuracy and speed of interpretation of graphical data. GV can be used to compare the effectiveness of different graphical techniques, graphing formats, variations in symbols and shading within a graph, graph size and display intensity. The tool has advantages over other methods by virtue of its objectivity and accuracy. It is designed to collect both survey and experimental data, offering the researcher a flexible and inexpensive method for presenting an S with a series of cards. It also allows Ss to be able to work with minimal interaction with and supervision from the investigator. The software tool and its operation are described.

Kamada, T. and S. Kawai (1991). "A General Framework for Visualizing Abstract Objects and Relations." ACM Transactions on Graphics **10**(1): 1-39
[Familiarity, Evaluation].

Pictorial representations significantly enhance our ability to understand complicated relations and structures, which means that information systems strongly require user interfaces that support the visualization of many kinds of information with a wide variety of graphical forms. At present, however, these difficult visualization problems have not been solved. We present a visualization framework for translating abstract objects and relations, typically represented in textual forms, into pictorial representations, and describe a general visualization interface based on this framework. In our framework, abstract objects and relations are mapped to graphical objects and relations by user-defined mapping rules. The kernel of our visualization process is to determine a layout of graphical objects under geometric constraints. A constraint-based object layout system named COOL has been developed to handle this layout problem. COOL introduces the concept of rigidity of constraints in order to reasonably handle a set of conflicting constraints by use of the least squares method. As applications of our system, we show the generation of kinship diagrams, list diagrams, Nassi-Shneiderman diagrams, and entity-relationship diagrams.

Leung, Y. K. and M. D. Apperley (1993). Towards the Metrication of Graphical Presentation Techniques for Large Data Sets. East-West International Conference on Human-Computer Interaction: Proceedings of the EWHCI'93
[Evaluation].

Rapid advances in communications and computer technologies in recent years have provided users with greater access to large volumes of data from computer-based information systems. While researchers have developed many novel techniques to overcome the problems associated with the presentation and navigation of large data sets on a limited display surface, the choice of a technique in a particular application remains very subjective. This paper proposes an evaluation framework E{cubed} which aims to provide a basis for the comparison of different presentation techniques, given the nature and characteristics of the data to be presented, and the interpretation required. E{cubed} focuses on three aspects of graphical data presentation: expressiveness, efficiency, and effectiveness. This framework lays the foundation for the development of a set of metrics to facilitate an objective assessment of presentation techniques.

Mercurio, P. J. and T. D. Erickson (1990). Interactive Scientific Visualization: An Assessment of a Virtual Reality System. Proceedings of IFIP INTERACT'90: Human-Computer Interaction 741-745
[Evaluation].

A virtual reality system, consisting of a head-mounted stereoscopic display and a computer-interfaced glove, was assessed by examining interaction with a 3-D model of the human brain. Interactions were recorded on videotape. Non-trivial user interface issues were identified, ranging from constraints imposed by the nature of the wearable interface hardware, to the choice of gestures for controlling the interaction, to problems with a metaphor used in the interface. Some possible solutions are discussed. Sound solutions to these problems, coupled with increases in the computational power of the underlying hardware, are needed for virtual reality to realize its immense potential for scientific visualization.

Neilsen, J. and R. Mack (1994). Usability Inspection Methods. New York, NY, John Wiley & Sons Inc.
[Evaluation].
1. Executive Summary Robert L. Mack, Jakob Nielsen
2. Heuristic Evaluation, Jakob Nielsen
3. The Pluralistic Usability Walkthrough: Coordinated Empathies, Randolph G. Bias
4. Inspections and Design Reviews: Framework, History, and Reflection, Dennis Wixon, Sandra Jones, Linda Tse, George Casaday
5. The Cognitive Walkthrough Method: A Practitioner's Guide Cathleen Wharton John Rieman, Clayton Lewis, Peter Polson
6. Formal Usability Inspections, Michael J. Kahn, Amanda Prail
7. Faster, Cheaper!! Are Usability Inspection Methods as Effective as Empirical Testing? Heather W. Desurvire
8. A Comparison of User Interface Evaluation Methods, Clare-Marie Karat
9. Evaluating High-Level Design: Synergistic Use of Inspection and Usability Methods for Evaluating Early Software Designs, Janice S. Bradford
10. Adding Value to Usability Testing, Patricia Brooks
11. Usability Problem Reports: Helping Evaluators Communicate Effectively with Developers, Robin Jeffries
12. Observing, Predicting, and Analyzing Usability Problems, Robert Mack, Frank Montaniz

13. The Role of Psychological Theory in Usability Inspection Methods, Cathleen Wharton, Clayton Lewis
14. Interface Design Guidance Systems, Louis A. Blatt, James F. Knutson
Bibliography
Author Index
Subject Index

Sutcliffe, A. G. and U. K. Patel (1993). The Three-Dimensional Graphical User Interface: Evaluation for Design Evolution. Proceedings of the HCI'93 Conference on People and Computers VIII 311-331
[Evaluation].

The design of a three-dimensional interactive graphical user interface for a medical knowledge based system is described. A prototype of the design has been developed and evaluated. The evaluation study investigated usability, and individual differences in patterns of interaction. It was found that there are individual differences in the way users explore three dimensional visualisations, and that usability is dependent on both the morphology (visualisation) and manipulations (interface functionality). While three-dimensional graphics can help reduce representational complexity, other forms of complexity are intrinsic to the medium and require design solutions. Implications of these findings for design evolution are discussed.

1 Introduction
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4.5 User Ratings and Opinions
5 Discussion
5.1 Information Structure of the Search Task
5.2 Instantiation of One Evaluation Task

V. Visualization Examples

Afsarmanesh, H. and D. McLeod (1989). "The 3DIS: An Extensible Object-Oriented Information Management Environment." ACM Transactions on Information Systems 7(4): 339-377
[Example].

The 3-Dimensional Information Space (3DIS) is an extensible object-oriented framework for information management. It is specifically oriented toward supporting the database requirements for data-intensive information system applications in which (1) information objects of various levels of abstraction an modalities must be accommodated, (2) descriptive and structural information (metadata) is rich and dynamic, and (3) users who are not database experts must be able to design, manipulate, and evolve databases. In response to these needs, the 3DIS provides an approach in which data and the descriptive information about data are handled uniformly in an extensible framework. The 3DIS provides a simple, geometric, and formal representation of data which forms a basis for understanding, defining, and manipulating databases. Several prototype implementations based upon the 3DIS have been designed and implemented and are in experimental use.

Anick, P. G., J. D. Brennan, R. A. Flynn, D. R. Hanssen, B. Alvey and J. M. Robbins (1990). A Direct Manipulation Interface for Boolean Information Retrieval via Natural Language Query. Proceedings of the Thirteenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 135-150
[Example].

This paper describes the design of a direct manipulation user interface for Boolean information retrieval. Intended to overcome the difficulties of manipulating explicit Boolean queries as well as the "black box" drawbacks of so-called natural language query systems, the interface presents a two-dimensional graphical representation of a user's natural language query which not only exposes heuristic query transformations performed by the system, but also supports query reformulation by the user via direct manipulation of the representation. The paper illustrates the operation of the interface as implemented in the AI-STARS full-text information retrieval system.

Belkin, N. J. and P. G. Marchetti (1990). Determining the Functionality and Features of an Intelligent Interface to an Information Retrieval System. Proceedings of the Thirteenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 151-177
[Evaluation, Example].

In this paper, we propose a method for specifying the functionality of an intelligent interface to large-scale information retrieval systems and for implementing those functions in an operational environment. The method is based on a progressive, three-stage model of intelligent information support; a high-level cognitive task analysis of the information retrieval problem; a low-level specification of the host system functionality; and, derivation of explicit relations between the system functions and the cognitive tasks. This method is applied, by example, in the context of the European Space Agency Information Retrieval Service, with some specific suggestions for implementation of a stage one intelligent interface to that system.

Boiko, V. B., P. P. Voroshko and A. J. Medinez (1991). Postprocessors for Visualization of Thermal and Strain State Calculations for Two- and Three-Dimensional Objects of Strained Solid Mechanics. First Moscow International HCI'91 Workshop Proceedings 102-103
[Example].

Mobile and reliable software has been developed for postprocessor visualization of the geometry of discrete models of strained solid mechanics 3-D problems and the results of their solution by the original FEM mixed schemes of high accuracy. IBM PC/XT/AT allow construction of central and parallel finite element (FE) model projections, representation of its topology and visualization of FE parameters, representation of scalar and vector fields on the surface of the body in the initial state and of that subjected to deformation. The postprocessor capabilities are shown using as an example visualizing of a nonsteady-state heating of the turbine shell of intricate shape at different moments of its service regime.

Card, S. K., G. G. Robertson and J. D. Mackinlay (1991). The Information Visualizer, An Information Workspace. Proceedings of ACM CHI'91 Conference on Human Factors in Computing Systems 181-188
[Example].

This paper proposes a concept for the user interface of information retrieval systems called an information workspace. The concept goes beyond the usual notion of an information retrieval system to encompass the cost structure of information from secondary storage to immediate use. As an implementation of the concept, the paper describes an experimental system, called the Information Visualizer, and its rationale. The system is based on (1) the use of 3D/Rooms for increasing the capacity of immediate storage available to the user, (2) the Cognitive Co-processor scheduler-based user interface interaction architecture for coupling the user to information agents, and (3) the use of information visualization for interacting with information structure.

Chalmers, M. (1993). Visualisation of Complex Information. East-West International Conference on Human-Computer Interaction: Proceedings of the EWHCI'93 38-50
[Example].

In information retrieval, sets of documents are stored and categorised in order to allow for search and retrieval. The complexity of the basic information is high, with representations involving thousands of dimensions. Traditional interaction techniques for such complex information therefore hide much of its complexity and structure, and offer access to it by means of isolated queries and word searches. Bead is a system which takes a complementary approach, as it builds and displays an approximate model of the document corpus in the form of a map or landscape constructed from the patterns of similarity and dissimilarity of the documents making up the corpus. In this paper, emphasis is given to the influences on and principles behind the design of the landscape model and the abandonment of a 'point cloud' model used in an earlier version of the system, rather than the more mathematical aspects of model construction.

Chalmers, M. and P. Chitson (1992). Bead: Explorations in Information Visualization. Proceedings of the Fifteenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 330-337
[Visibility, Example].

We describe work on the visualization of bibliographic data and, to aid in this task, the application of numerical techniques for multidimensional scaling. Many areas of scientific research involve complex multivariate data. One example of this is Information Retrieval. Document comparisons may be done using a large number of variables. Such conditions do not favour the more well-known methods of visualization and graphical analysis, as it is rarely feasible to map each variable onto one aspect of even a three-dimensional, coloured and textured space. Bead is a prototype system for the graphically-based exploration of information. In this system, articles in a bibliography are represented by particles in 3-space. By using physically-based modelling techniques to take advantage of fast methods for the approximation of potential fields, we represent the relationships between articles by their relative spatial positions. Inter-particle forces tend to make similar articles move closer to one another and dissimilar ones move apart. The result is a 3D scene which can be used to visualize patterns in the high-D information space.

Carlsson, C. and E. F. Lennart (1993). Integrated CSCW Tools within a Shared 3D Virtual Environment. Proceedings of ACM INTERCHI'93 Conference on Human Factors in Computing Systems 513
[Example].

With the advance of computer graphics hardware and computer communication technology it is now possible to build personal interactive 3D interfaces. Our research goal is to use this technology to create CSCW environments. We specifically address three intimately connected problem areas: * awareness (what are other users doing?) * focus (where is my attention directed?) * interaction metaphors (how do I do something?) Our approach is to let each user be represented by a 3D icon ("body icon" and graphically model the user's input devices in 3D space. Users navigate between applications in 3D space and can meet and collaborate in the environment. There is a direct correspondence between a user's body icon, input devices and the actions taken by the user. We claim that this gives users a more detailed and natural understanding of other users activities than in conventional CSCW systems. By using direct (real world) metaphors in the interaction with applications, it is our hope that the cognitive load on the users is reduced and the awareness and focus effects are increased.

Chuah, M. C., S. F. Roth, J. Kolojejchick, J. Mattis and O. Juare (1995). SageBook: Searching Data-Graphics by Content. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 338-345
[Example].

Currently, there are many hypertext-like tools and database retrieval systems that use keyword search as a means of navigation. While useful for certain tasks, keyword search is insufficient for browsing databases of data-graphics. SageBook is a system that searches among existing data-graphics, so that they can be reused with new data. In order to fulfill the needs of retrieval and reuse, it provides: 1) a direct manipulation, graphical query interface; 2) a content description language that can express important relationships for retrieving data-graphics; 3) automatic description of stored data-graphics based on their content; 4) search techniques sensitive to the structure and similarity among data-graphics; 5) manual and automatic adaptation tools for altering data-graphics so that they can be reused with new data.

Cox, K. C. and S. G. Eick (1995). " 3D Displays of Internet Traffic." IEEE: 129-131

[Example].

Cugini, J., C. Piatko and S. Laskowski (1997). Interactive 3D Visualization for Document Retrieval. The National Institute of Standards and Technology
[Example].

The availability of large collections of documents coupled with powerful search and retrieval algorithms provides the opportunity for people to access large sets of relevant documents in electronic form. However, often a user query can result in hundreds of potentially useful documents returned by the system. Our hypothesis is that interactive 3D graphics techniques can be used to help the user comprehend and filter such result sets. We describe some prototypes developed at NIST in pursuit of these goals and discuss associated design issues, such as icon appearance, layout within 3D space, and interaction mechanisms.

Eick, S. G. (1994). Data Visualization Sliders. Proceedings of the ACM Symposium on User Interface Software and Technology 119-120
[Identifiability: Dimensionality, Example].

Computer sliders are a generic user input mechanism for specifying a numeric value from a range. For data visualization, the effectiveness of sliders may be increased by using the space inside the slider as an interactive color scale, a barplot for discrete data, and a density plot for continuous data. The idea is to show the selected values in relation to the data and its distribution. Furthermore, the selection mechanism may be generalized using a painting metaphor to specify arbitrary, disconnected intervals while maintaining an intuitive user-interface.

Feiner, S., B. MacIntyre, M. Haupt and E. Solomon (1993). "Windows on the World: 2D Windows for 3D Augmented Reality." Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 145-155
[Example].

We describe the design and implementation of a prototype heads-up window system intended for use in a 3D environment. Our system includes a see-through head-mounted display that runs a full X server whose image is overlaid on the user's view of the physical world. The user's head is tracked so that the display indexes into a large X bitmap, effectively placing the user inside a display space that is mapped onto part of a surrounding virtual sphere. By tracking the user's body, and interpreting head motion relative to it, we create a portable information surround that envelopes the user as they move about. We support three kinds of windows implemented on top of the X server: windows fixed to the head-mounted display, windows fixed to the information surround, and windows fixed to locations and objects in the 3D world. Objects can also be tracked, allowing windows to move with them. To demonstrate the utility of this model, we describe a small hypermedia system that allows links to be made between windows and windows to be attached to objects. Thus, our hypermedia system can forge links between any combination of physical objects and virtual windows.

Hemmje, M. (1995). Lyberworld -- A 3D Graphical User Interface for Fulltext Retrieval. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 417-418
[Example].

LyberWorld is a prototype IR user interface. It implements visualizations of an abstract information space: fulltext. The video demonstrates a visual user interface for the probabilistic fulltext retrieval system INQUERY. Visualizations are used to communicate information search and browsing activities in a natural way by applying metaphors of spatial navigation in abstract information spaces. Visualization tools for exploring information spaces and judging relevance of information items are introduced and an example session demonstrates the prototype. The presence of a spatial model in the user's mind is regarded as an essential contribution towards natural interaction and reduction of cognitive costs during retrieval dialogues.

Hinckley, K., R. Pausch, J. C. Goble and N. F. Kassell (1994). Passive Real-World Interface Props for Neurosurgical Visualization. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 452-458
[Example].

We claim that physical manipulation of familiar real-world objects in the user's real environment is an important technique for the design of three-dimensional user interfaces. These real-world passive interface props are manipulated by the user to specify spatial relationships between interface objects. By unobtrusively embedding free-space position and orientation trackers within the props, we enable the computer to passively observe a natural user dialog in the real world, rather than forcing the user to engage in a contrived dialog in the computer-generated world. We present neurosurgical planning as a driving application and demonstrate the utility of a head viewing prop, a cutting-plane selection prop, and a trajectory selection prop in this domain. Using passive props in this interface exploits the surgeon's existing skills, provides direct action-task correspondence, eliminates explicit modes for separate tools, facilitates natural two-handed interaction, and provides tactile and kinesthetic feedback for the user. Our informal evaluation sessions have shown that with a cursory introduction, neurosurgeons who have never seen the interface can understand and use it without training..

Lay, K. and A. Brunn (1989). An Integrated Window Based User Interface for Engineering Design Using 3-D Graphics. Proceedings of the Third International Conference on Human-Computer Interaction 302-312
[Example].

In this paper we present a tool for the efficient and rapid creation of user interfaces for CAE applications, e.g. interactive modeling or robotics programming. The tool combines 3D-graphics and window based dialog elements such as menus, icons or input fields. This enables the user to get a uniform and flexible control of his application. The tool consists of five components which are described as well as their interaction: a dialog manager, a 3D-graphic kernel system, a construction language for user interfaces, an application interface and a graphic editor for user interfaces.

Lokuge, I. and S. Ishizaki (1995). GeoSpace: An Interactive Visualization System for Exploring Complex Information Spaces. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 409-414
[Example].

This paper presents a reactive interface display which allows information seekers to explore complex information spaces. We have adopted information seeking dialogue as a fundamental model of interaction and implemented a prototype system in the mapping domain -- GeoSpace -- which progressively provides information upon a user's input queries. Domain knowledge is represented in a form of information presentation plan modules, and an activation spreading network technique is used to determine the relevance of information. The reactive nature of the activation spreading network, combined with visual design techniques, such as typography, color and transparency enables the system to support the information seeker in exploring the complex information space. The system also incorporates a simple learning mechanism which enables the system to adapt the display to a particular user's preferences. GeoSpace allows users to rapidly identify information in a dense display and it can guide a users' attention in a fluid manner while preserving overall context.

Mariani, J. A. and R. Lougher (1992). "TripleSpace: An Experiment in a 3D Graphical Interface to a Binary Relational Database." Interacting with Computers **4**(2): 147-162
[Example].

Novel techniques of data visualization will be required to take full advantage of the advanced human-computer interaction technology now being developed as part of the virtual reality movement. In particular, meaningful three-dimensional representations will be of interest to users wishing to explore the data topology. An experimental system which offers a three-dimensional topology is presented in this paper; three sets of data representing interesting situations are described and viewed through the system.

Matsuoka, S., S. S. Kamada and A. Yonezawa (1992). "A General Framework for Bidirectional Translation between Abstract and Pictorial Data." ACM Transactions on Information Systems **10**(4): 408-437
[Example].

The merits of direct manipulation are now widely recognized. However, direct manipulation interfaces incur high cost in their creation. To cope with this problem, we present a model of bidirectional translation between pictures and abstract application data, and a prototype system, TRIP2, based on this model. Using this model, general mapping from abstract data to pictures and from pictures to abstract data is realized merely by giving declarative mapping rules, allowing fast and easy creation of direct manipulation interfaces. We apply the prototype system to the generation of the interfaces for kinship diagrams, Graph Editors, E-R diagrams, and an Othello game.

Mukherjea, S. and J. D. Foley (1994). Navigational View Builder: A Tool for Building Navigational Views of Information Spaces. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 289-290
[Example].

Overview node and link diagrams are one of the best tools for context and orientation in hypermedia systems. To be really effective these need to show not only the node and link topology but more information about the underlying information space. The Navigational View Builder allows the designer or the user to control the dynamic binding between the visual properties of the overview diagrams and the underlying information. Dynamic binding can also be used for forming fish-eye views. Finally, by combining this method with force-based graph-drawing algorithms, visual clusters of related nodes based on various similarity metrics can be formed.

Mukherjea, S., J. D. Foley and S. Hudson (1995). Visualizing Complex Hypermedia Networks through Multiple Hierarchical Views. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 331-337
[Structural Integrity, Example].

Our work concerns visualizing the information space of hypermedia systems using multiple hierarchical views. Although overview diagrams are useful for helping the user to navigate in a hypermedia system, for any real-world system they become too complicated and large to be really useful. This is because these diagrams represent complex network structures which are very difficult to visualize and comprehend. On the other hand, effective visualizations of hierarchies have been developed. Our strategy is to provide the user with different hierarchies, each giving a different perspective to the underlying information space to help the user better comprehend the information. We propose an algorithm based on content and structural analysis to form hierarchies from hypermedia networks. The algorithm is automatic but can be guided by the user. The multiple hierarchies can be visualized in various ways. We give examples of the implementation of the algorithm on two hypermedia systems.

Nowell, L. T. and E. A. Fox (1995). Envision: Information Visualization in a Digital Library. Proceedings of the Eighteenth Annual International ACM SIGIR Conference on Research and Development in Information Retrieval 365
[Example].

Envision is a multimedia digital library of computer science literature, with full-text searching and full-content retrieval capabilities, serving computer science researchers, teachers, and students at all levels of expertise. The most unusual feature of Envision is its Graphic View window, which provides powerful information visualization facilities that enable users to explore patterns in the literature. that represent documents. Users have control over the semantics of six graphical devices: icon position along the x-axis and y-axis, the alphanumeric icon label, icon size, icon color, and icon shape. These graphical devices may represent a number of document attributes: probable relevance to query, publication year, document type (e.g., text, video, hypermedia), document size, number of sources, author names, and index terms. Working in tandem with the Graphic View, the Item Summary window presents bibliographic information for icons selected by the user. Document content is presented on demand using Mosaic and a suite of related viewers. Recent studies show strong user interest and satisfaction, and minor changes they have suggested are being incorporated into newer versions of the interface software. Implementation efforts have led to an X Motif version of the Envision interface, which will be shown with a sample of the overall digital library collection.

Phillips, M. D., J. E. Allison and V. S. Dodd (1983). An Assessment of Computer Generated Space Situation Map Projections. Proceedings of ACM CHI'83 Conference on Human Factors in Computing Systems 135-138
[Example].

C{sup:3} environments have increasingly incorporated computer controlled maps as decision aids. The design of map displays in space oriented C{sup:3} system has taken on greater importance due to the complex spatial relationships among orbiting objects. The large number of objects orbiting the globe and their great speeds further complicates efforts to quickly and accurately portray their positions graphically. This paper describes an experimental plan aimed at evaluating a new 2D/3D "hybrid" space situation map display. The Hybrid display is created by opening a globe at the south pole and flattening it into a platter. A third dimension is obtained by tilting the platter. It was hypothesized that the Hybrid display would offer an advantage to C{sup:3} system operators and analysts dealing with three dimensional problems. The test plan focuses on perceptual parameters and user preference issues concerning conventional and Hybrid display techniques. The results of this study will be examined to direct future work on dynamic displays, and the impact of display design approach on cognitive performance.

Reiss, S. P. (1993). Presentation and Editing of Structured 3-D Graphics. Proceedings of the Fifth International Conference on Human-Computer Interaction 397-402 [Identifiability: Dimensionality, Example].

This paper provides an overview of our efforts at providing high-quality, 3-D visualizations of information about programs. This data is generated by querying the different information sources through a single object-oriented database schema. The result of the query is a set of abstraction objects that are then mapped, through a set of user-definable translations, into a set of abstract graphical objects that represent the display. A separate package handles layout, constraints, and presentation of these graphical objects. The resultant display is interactive at three levels. Syntactic interactions allow the user to pan, zoom and fly around in 3-D space. Semantic interactions allow user actions to affect the translations from abstraction objects into abstract graphical objects and to change the set of abstraction objects by modifying the initial query.

Rennison, E. (1994). Galaxy of News: an Approach to Visualizing and Understanding Expansive New Landscapes. UIST ACM Symposium on User Interface Software and Technology 3-12 [Example].

The Galaxy of News system embodies an approach to visualizing large quantities of independently authored pieces of information, in this case news stories. At the heart of this system is a powerful relationship construction engine that constructs an associative relation network to automatically build implicit links between related articles. To visualize these relationships, and hence the news information space, the Galaxy of News uses pyramidal structuring and visual presentation, semantic zooming and panning, animated visual cues that are dynamically constructed to illustrate relationships between articles, and fluid interaction in a three dimensional information space to browse and search through large databases of news articles. The result is a tool that allows people to quickly gain a broad understanding of a news base by providing an abstracted presentation that covers the entire information base, and through interaction, progressively refines the details of the information space. This research has been generalized into a model for news access and visualization to provide automatic construction of news information spaces and derivation of an interactive news experience.

Robertson, G. G. and J. D. Mackinlay (1993). The Document Lens. Proceedings of the ACM SIGGRAPH Symposium on User Interface Software and Technology 101-108 [Familiarity, Example].

This paper describes a general visualization technique based on a common strategy for understanding paper documents when their structure is not known, which is to lay the pages of a document in a rectangular array on a large table where the overall structure and distinguishing features can be seen. Given such a presentation, the user wants to quickly view parts of the presentation in detail while remaining in context. A fisheye view or a magnifying lens might be used for this, but they fail to adequately show the global context. The Document Lens is a 3D visualization for large rectangular presentations that allows the user to quickly focus on a part of a presentation while continuously remaining in context. The user grabs a rectangular lens and pulls it around to focus on the desired area at the desired magnification. The presentation outside the lens is stretched to provide a continuous display of the global context. This stretching is efficiently implemented with affine transformations, allowing text documents to be viewed as a whole with an interactive visualization.

Sarkar, M., S. S. Snibbe, O. J. Tversky and S. P. Reiss (1993). Stretching the Rubber Sheet: A Metophor for Visualizing Large Layouts on Small Screens. Proceedings of the ACM SIGGRAPH Symposium on User Interface Software and Technology 81-91
[Example].

We propose the metaphor of rubber sheet stretching for viewing large and complex layouts within small display areas. Imagine the original 2D layout on a rubber sheet. Users can select and enlarge different areas of the sheet by holding and stretching it with a set of special tools called handles. As the user stretches an area, a greater level of detail is displayed there. The technique has some additional desirable features such as areas specified as arbitrary closed polygons, multiple regions of interest, and uniform scaling inside the stretched regions.

Shaw, C. and M. Green (1994). "Two-Handed Polygonal Surface Design." Proceedings of the ACM Symposium on User Interface Software and Technology: 205-212
[Input Compatibility, Example].

This paper describes a Computer Aided Design system for sketching free-form polygonal surfaces such as terrains and other natural objects. The user manipulates two 3D position and orientation trackers with three buttons, one for each hand. Each hand has a distinct role to play, with the dominant hand being responsible for picking and manipulation, and the less-dominant hand being responsible for context setting of various kinds. The less-dominant hand holds the workpiece, sets which refinement level that can be picked by the dominant hand, and generally acts as a counterpoint to the dominant hand. In this paper, the architecture of the system is outlined, and a simple surface is shown.

Stoakley, R., M. J. Conway and R. Pausch (1995). Virtual Reality on a WIM: Interactive Worlds in Miniature. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 265-272
[Example].

This paper explores a user interface technique which augments an immersive head tracked display with a hand-held miniature copy of the virtual environment. We call this interface technique the Worlds in Miniature (WIM) metaphor. In addition to the first-person perspective offered by a virtual reality system, a World in Miniature offers a second dynamic viewport onto the virtual environment. Objects may be directly manipulated either through the immersive viewport or through the three-dimensional viewport offered by the WIM. which Worlds in Miniature can act as a single unifying metaphor for such application independent interaction techniques as object selection, navigation, path planning, and visualization. The WIM metaphor offers multiple points of view and multiple scales at which the user can operate, without requiring explicit modes or commands. Miniature metaphor quickly and that physical props are helpful in manipulating the WIM and other objects in the environment.

Storey, N. and J. F. Craine (1984). Interactive Stereoscopic Computer Graphic Display Systems. Proceedings of IFIP INTERACT'84: Human-Computer Interaction 163-168
[Example].

Conventional CRT displays give only a two dimensional representation of three dimensional objects which means that depth information can be presented only indirectly, using such techniques as hidden line removal, shading and object rotation. Improved perception of 3D images is possible by presenting to the viewer a stereoscopic pair of two-dimensional images. To be truly effective, the image presented by a stereoscopic display should change as the viewing point moves. Such a system requires a knowledge of the user's head position and orientation in order to compute the view to be presented to each eye. The paper describes an approach to a system of this type.

Strausfeld, L. (1995). Financial Viewpoints: Using Point-of-View to Enable Understanding of Information. Proceedings of ACM CHI'95 Conference on Human Factors in Computing Systems 208-209
[Example].

This paper presents Financial Viewpoints, an experimental interactive 3D information space that spatially and volumetrically represents a portfolio of seven mutual funds. 3D point-of-view is used to represent context and context shifts in the information and to allow users to view multiple representations of the information in a single, continuous environment. This project is the first in a larger and ongoing research effort to explore the notion of embodied virtual space.

Sugiyama, K. and K. Misue (1991). "Visualization of structural information: Automatic drawing of compound digraphs." IEEE Transactions on Systems, Man, and Cybernetics **21**(4): 876-892
[Example].

Presents an automatic method for drawing compound digraphs that contain both inclusion edges and adjacency edges. In the method, vertices are drawn as rectangles, inclusion edges by the geometric inclusion among the rectangles, and adjacency edges by arrows connecting them. Readability elements such as drawing conventions and rules are identified, and a heuristic algorithm to generate readable diagrams is developed. Three applications demonstrate the effectiveness of the algorithm. The utilization of curves is investigated to improve the quality of diagrams. A possible set of command primitives for progressively organizing structures within this graph formalism is also discussed.

Williams, M. G., S. Smith and G. Pecelli (1990). "Computer-Human Interface Issues in the Design of an Intelligent Workstation for Scientific Visualization." ACM SIGCHI Bulletin **21**(4): 44-49

[Example].

The long-range goal of our research is to create an intelligent assistant for interactive scientific data visualization via both sight and sound. There are a variety of computer-human interface (CHI) issues that are unique to our approach to interactive visualization. It is upon these issues that we focus here. In this paper, we: (1) describe the approach to interactive visualization taken by the project which is the context of our work; (2) specify the CHI issues that are peculiar to this approach; (3) summarize the current capabilities of our workstation for performing human factors experiments; (4) describe the research plan we have developed for learning how to provide a user with intelligent assistance for dealing with those issues; (5) present a representative pilot study that has contributed useful information; (6) summarize the results of our pilot studies; and (7) discuss the direction of our future work. We do not claim to be solving the general case of how to provide intelligent assistance for scientific visualization. We do, however, expect that the progress we make in one visualization environment will contribute to understanding of the general case.

Williamson, J. E. (1993). Hyper3D. Proceedings of ACM Hypertext'93 -- Posters 22
[Example].

Hyper3D, currently in BETA, is an attempt to combine the beauty and significance of antique stereocards with the ease of use and organizational power of hypertext and the added dimension of stereoscopic 3D computer displays. Both the digitized stereocards and the hypertext are presented in stereoscopic 3D. The collection of technologies that have become known as "virtual reality" will incorporate text either directly as documents or indirectly as menus or organizational structures. Due to the very nature of the display technologies used, these text items will be presented in stereoscopic 3D. The effect of viewing, reading and comprehending text that is presented stereoscopically is a human factors question that has not yet been fully addressed. With rare exceptions, current head-mounted displays (HMDs) do not yet provide sufficient resolution to read text. In fact most current HMDs leave the user legally blind, with 20/200 to 20/400 vision. However, by using a non-immersive, stereoscopic computer display that is both affordable and readable, some of the initial human factors and human perception issues that relate to stereoscopic text can be addressed. Hyper3D, in addition to being a marketable product, is rich and flexible enough to serve as a test bed to examine these issues.

Wilson, S. (1994). Memory Map: An Interactive Installation that Maps Memory Space to Physical Space. Proceedings of ACM CHI'94 Conference on Human Factors in Computing Systems 55-56
[Example].

Memory Map is an interactive installation in which the memories, reflections, and anticipations of visitors become critical aesthetic elements. The physical space of a hall becomes a metaphor for the collective memory space of those who have visited the installation -- for example, with the voices of those older than the present viewer coming from in front and those younger coming from behind. The installation explores interface issues of 3-D sound and the mapping of conceptual abstractions to physical space.

Wise, J. A. and e. al. (1995). Visualizing the Nonvisual: Spatial Analysis and Interaction with Information from Text Documents. Proceedings of Information Visualization Symposium, Los Alamitos, California, IEEE Computer Society Press 51-58
[Example].

Wise, J. A., J. J. Thomas, K. Pennock, D. Lantrip, M. Pottier, A. Schur and V. Crow (1995). Visualizing the Non-Visual: Spatial Analysis and Interaction with Information from Text Documents. Information Visualization, IEEE 51-58
[Example].

Zizi, M. and M. Beaudouin-Lafon (1994). Accessing Hyperdocuments through Interactive Dynamic Maps. Proceedings of the ECHT'94 European Conference on Hypermedia Technologies 126-135
[Example].

We propose a new navigation paradigm based on a spatial metaphor to help users access and navigate within large sets of documents. This metaphor is implemented by a computer artifact called an Interactive Dynamic Map (IDM). An IDM plays a role similar to the role of a real map with respect to physical space. Two types of IDMs are computed from the documents: Topic IDMs represent the semantic contents of a set of documents while Document IDMs visualize a subset of documents such as those resulting from a query. IDMs can be used for navigating, browsing, and querying. They can be made active, they can be customized and they can be shared among users. The article presents the SHADOCS document retrieval system and describes the role, use and generation of IDMs in SHADOCS.